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Magnetic Field in the Universe

Nguyen Thi Thao Trang, Peter Lott and Quynh Lan Nguyen
Phenikaa Institute for Advanced Study, Phenikaa University
Yen Nghia, Hanoi 12116, Vietnam

E-mail: `lan.nguyenquynh@phenikaa-uni.edu.vn`

Abstract. Magnetic fields permeate the universe and influence physical processes, from compact objects to large cosmic structures. Unlike electric fields, magnetic fields are closely tied to space-time dynamics, governing charged particle motion and producing radiation such as synchrotron and curvature emission. On intergalactic scales, magnetic fields are reshaped during galaxy mergers. Gravitational forces drive turbulence, shock waves, and gas inflows that amplify and reorganize magnetic fields. Radio synchrotron emission and polarization mapping observations reveal strong, coherent fields in tidal tails, bridges, and star-forming regions. These fields regulate star formation, guide cosmic ray transport, and contribute to the magnetization of the intergalactic medium. On more minor scales, in neutron stars and especially magnetars, magnetic fields reach strengths far beyond those produced in terrestrial labs. These extreme fields deform the solid crust of the star, potentially generating continuous gravitational waves through persistent asymmetric mass distributions. Simulations using general relativistic magnetohydrodynamics and crustal elasticity are essential to understanding these signals and probing the internal physics of neutron stars. This paper reviews advances in the study of magnetic fields in merging galaxies and magnetars, focusing on physical mechanisms and simulation techniques, including the velocity gradient technique and GRMHD modeling. Future advances in simulation techniques and observatories promise to deepen our understanding of the role of magnetic fields across the cosmos.

1. Introduction

Magnetic fields are crucial to various astrophysical phenomena, influencing cosmic systems across scales. They play a key role in the dynamics and evolution of galaxy mergers and neutron stars. Understanding the behavior of magnetic fields in these extreme environments is essential for advancing our understanding of the universe. On large scales, magnetic fields significantly impact galaxy mergers. Gravitational interactions cause shock waves, turbulence, and gas inflows, which can amplify and restructure magnetic fields. Radio synchrotron emission and polarization maps reveal that magnetic fields in merging systems remain organized, even in tidal features such as stellar streams and bridges [1]. These fields affect star formation, cosmic-ray propagation, and other astrophysical processes, requiring high-resolution simulations and detailed observational data [2; 3]: large-scale dynamo processes and local turbulence drive magnetic field evolution in galaxy mergers. Gas flows interacting with the magnetic field can amplify it, while shock fronts and turbulence further reorganize it [4]. These fields are essential for star formation, cosmic ray transport, and energy balance. Advanced radio telescopes such as the Very Large Array and the Square Kilometer Array (SKA) offer the resolution needed to study these fields [5]. Electromagnetic observations are based on a variety of detectors. In addition to radio telescopes, the Chandra X-ray Observatory provides insights into high-energy environments like magnetars.

At the same time, the Hubble Space Telescope studies galactic morphology and magnetic field distribution [6; 7]. ALMA is helpful for high-resolution observations of molecular clouds and star-forming regions [8], and the Fermi Gamma ray Space Telescope detects emissions driven by magnetic fields in systems such as active galactic nuclei and magnetars [9]. LOFAR excels at observing magnetic fields in the intergalactic medium and galaxy clusters [10].

Magnetic fields in neutron stars, especially magnetars, are crucial to understanding these astrophysical phenomena. Magnetars have powerful magnetic fields that deform their crusts, forming *magnetar mountains.* These deformations emit continuous gravitational waves, offering a new way to probe neutron star interiors. These phenomena are studied using general relativistic magnetohydrodynamics (GRMHD) simulations [11; 12]. Magnetar magnetic field interactions with plasma are modeled using magnetohydrodynamics (MHD). As the magnetic field evolves, it exerts pressure on the crust, causing localized deformations, which in turn generate gravitational waves detectable by interferometers like the Laser Interferometry Gravitational-wave Observatory (LIGO), Virgo, and KAGRA. Comparison of detected signals with theoretical models provides insight into the magnetic field of the neutron star and its crustal structure [13; 14; 15; 16].

The remainder of the paper is structured as follows. Section II focuses on the role of magnetic fields in galaxy mergers, discussing the processes through which magnetic fields are amplified and reorganized during galaxy interactions, and their influence on star formation, cosmic-ray dynamics, and the overall evolution of merging systems. Section III transitions to the study of magnetars, where we investigate the magnetic field characteristics of these neutron stars, the formation of magnetar mountains, and the generation of gravitational waves due to crustal deformations. This outline aims to provide a detailed examination of magnetic field phenomena across various astrophysical contexts. We conclude by forecasting the prevalence of magnetic field studies in future astrophysical research, emphasizing their increasing importance in understanding a wide array of cosmic phenomena.

2. Magnetic Signatures of Merging Galaxies

Galaxy mergers constitute a fundamental mechanism in the broader context of cosmic evolution, and as such the investigation of magnetic fields within merging systems is of considerable astrophysical interest. These magnetic field studies offer critical insights into the dynamical processes that drive galactic evolution and the formation of relativistic jets [17]. Moreover, interactions between the magnetic fields of merging galaxies and those of the interstellar medium, as well as with magnetic fields in neighboring and cluster galaxies, serve to enhance our understanding of the formation, evolution, and morphology of large-scale structures in the universe. During the merging of galaxies, gravitational interactions between galaxies lead to dramatic changes in morphology, star formation activity, gas dynamics, and magnetic field structure. These interactions not only distort galactic disks, but also amplify and reorganize magnetic fields on both local and global scales.

In order to probe these physical systems, it is useful to have a method to trace the magnetic field lines. The velocity gradient technique (VGT) is based on the anisotropy found in magnetohydrodynamic turbulence. In MHD turbulence, turbulent eddies tend to align along magnetic-field lines, particularly when examined in the local frame of reference. This anisotropic behavior is quantified by the relation [18]:

$$l_{\parallel} = L_{\rm inj} \left(\frac{l_{\perp}}{L_{\rm inj}} \right)^{\frac{2}{3}} M_A^{-4/3}, \quad M_A \leq 1, \tag{1}$$

where $l_{\parallel}$ and $l_{\perp}$ are the parallel and perpendicular scales concerning the local magnetic field. The Alfvén Mach number is given by $M_A = v_{\rm inj}/v_A$, with $v_{\rm inj}$ being the injection velocity and v_A the Alfvén speed.

The velocity gradients have proven effective in tracking magnetic fields in a variety of astrophysical contexts, including diffuse interstellar medium, molecular clouds [19], and Seyfert galaxies [20], and for the more complex dynamical environment such as the Centaurus galaxy merger [18].

By comparing velocity gradient directions with dust polarization vectors, we evaluated how well the VGT performed in tracing magnetic-field morphology under merger-driven turbulence. Our results show general statistical agreement, though local discrepancies, regions of misalignment, and anti-alignment, also emerge. Drawing on earlier findings, we interpret these as possible signatures of outflows or shock compression [21].

This comparison offers new insight into the magnetized ISM in merging galaxies and highlights regions where VGT remains reliable even when traditional tracers are absent. Future work should leverage higher signal-to-noise observations and include synchrotron polarization to further probe these effects [22].

Magnetic fields in merging galaxies are studied using several techniques. Radio synchrotron emission traces relativistic electrons spiraling around magnetic field lines. Faraday rotation provides the line-of-sight magnetic field strength and direction, as demonstrated in previous studies [23]. Furthermore, polarized radio emission reveals the coherence and orientation of the magnetic field [24]. Strong synchrotron and polarized emission is frequently observed in tidal features such as bridges and tails, as seen in the Antennae and Taffy Galaxies [25; 26], highlighting the persistence of coherent magnetic fields even during violent interactions.

Understanding magnetic field evolution in galaxy mergers is critical for regulating star formation through magnetic pressure and gas confinement, shaping cosmic-ray propagation and feedback processes [27], and seeding the intergalactic medium with magnetic fields through outflows and tidal stripping. Modern magnetohydrodynamic simulations are now capable of modeling these complex interactions, including the effects of cosmic rays and radiative feedback. Upcoming radio facilities, such as the SKA, are expected to revolutionize our ability to map magnetic fields in merging galaxies with unprecedented resolution and sensitivity [24; 5].

3. Magnetars

Neutron stars, dense remnants of massive stellar collapses, exhibit some of the most extreme physical conditions known in the universe, with densities exceeding those of atomic nuclei and magnetic fields that can surpass $10^{15}\,\mathrm{G}$ [28; 29]. A subset of neutron stars, known as *magnetars*, has the strongest magnetic fields observed in nature [30]. These immense magnetic fields are widely believed to be responsible for the high-energy phenomena observed in soft gamma-ray repeaters and anomalous X-ray pulsars [31]. In addition to their high-energy electromagnetic emissions, magnetars are also predicted to be sources of gravitational waves due to crustal deformations—commonly referred to as "mountains"—induced by magnetic and rotational stresses [32; 33]. Such deformations can generate a nonspherical mass distribution that evolves, producing a quadrupole mass moment capable of emitting gravitational radiation [34]. The interaction between magnetic fields and the elastic response of the neutron star crust governs the formation of magnetar mountains. As the magnetic field evolves, it applies anisotropic stresses to the crust, which can result in localized deformations [13; 35]. The longevity and magnitude of such deformations depend on the crust's shear modulus, breaking strain, and thermal characteristics [36]. If the mountain remains stable on astrophysically relevant timescales, the resulting quadrupole could generate a detectable gravitational wave signal, particularly by ground-based detectors such as LIGO, Virgo, and KAGRA [37; 38]. The detection of such a pattern would provide a direct observational window into the internal structure of magnetars.

For certain polytric equations of state, the threshold accretion rate required for sustained gravitational wave emission from such deformations is given by (See reference [39]):

$$\dot{M} > \dot{M}_{cric} = 1.8 \times 10^{-2} M_{1.4}^{-5/3} B_{15}^{2} R_{12}^{6} P_{1}^{-7/3} M_{\odot} s^{-1}, \tag{2}$$

where the radius R, mass$M$, magnetic field B, and spin period P of the star are scaled, respectively, as:

$$R_{12} = \frac{R}{12\text{km}}, M_{1.4} = \frac{M}{1.4 M_{\odot}}, B_{15} = \frac{B}{10^{15}\text{G}}, P_{1} = \frac{P}{1\text{ms}}. \tag{3}$$

This equation suggests a strong dependence on the deformed region's mass, magnetic field strength, radius, and characteristic density. Simulating these phenomena requires modeling the interaction between magnetic fields, fluid dynamics, and crustal elasticity in a relativistic framework. General Relativistic Magnetohydrodynamics provides a robust toolkit for this modeling [11; 12]. Codes like `Athena++` [40] and `HAM-R` [41]are well-suited for high-resolution GRMHD simulations in curved spacetime and their modeling of accretion flow. `Athena++` has been used to study the poloidal and toroidal evolution of spherically symmetric magnetized systems [42; 43]. Nevertheless, the incorporation of mountains into such simulations remains a non-trivial challenge. Achieving full GRMHD simulations of mountains on magnetars could provide critical insights into their viability as persistent sources of continuous gravitational waves.

With the continued advancement of gravitational wave detection technologies and numerical modeling capabilities, researchers can increasingly explore the whole parameter space associated with magnetar deformation. This progress enhances our understanding of magnetar physics and provides a promising avenue for detecting gravitational wave signals rooted in the internal mechanics of neutron stars.

4. Conclusion

Magnetic fields play a vital role in shaping the dynamics and evolution of the cosmos, and this shaping can be probed via both observation and advanced simulations. In galaxy mergers, the amplification and reorganization of magnetic fields due to gravitational interactions, turbulence, and shock waves significantly affect processes like star formation and cosmic ray propagation. As highlighted by studies such as [1], [2], and [3], radio synchrotron emission and polarization mapping have revealed coherent magnetic fields even in the tidal features of merging systems, such as stellar streams and bridges. These fields serve as a key regulatory mechanism in galaxy evolution, providing essential insights into the role of magnetic fields in shaping large-scale cosmic structures [27; 44].

Theoretical models, including those that use the velocity gradient technique, further our understanding of the magnetic field evolution in galaxy mergers, due to their ability to simulate turbulence in the interstellar medium, shock fronts, and the amplification and reorganization of magnetic fields, supported by observational data from advanced radio telescopes such as the Very Large Array and the Square Kilometer Array [5]. The VGT has proven particularly effective in tracing magnetic fields in disturbed galaxies, providing a novel means of mapping magnetic structures without more traditional tracers [13].

In neutron stars, particularly magnetars, studying magnetic fields may help illuminate the physics governing these stellar remnants. [13] and [12] have shown that immense magnetic fields of magnetars exert stresses on the star's crust, leading to deformations that may produce gravitational waves. Theoretical predictions and simulations [32; 33] suggest that these deformations may generate detectable gravitational wave signals, offering a novel method to investigate the interior structure of magnetars. Recent advances in general relativistic magnetohydrodynamics simulations, such as those described by [11] and [45], are helping to refine these models, providing deeper insight into the mechanics of magnetar crusts and the associated gravitational wave emissions.

Magnetic fields are not just passive byproducts of astrophysical processes; they are active agents shaping the dynamics of cosmic systems. In the future, magnetic fields will be an essential probe of astrophysical phenomena. Theoretical advances, coupled with high-resolution simulations and observational data, continue to enhance our ability to model these phenomena. The future of this research lies in next-generation observatories, like the SKA, and gravitational wave detectors such as LIGO, Virgo, and KAGRA, which will enable us to explore heavily magnetized systems with unprecedented sensitivity and precision. As these technologies evolve, they promise to deepen our understanding of the universe's most extreme and enigmatic systems, from merging galaxies to the interiors of magnetars.

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