EVOLUTION OF MAGNETIC FIELD AROUND NEUTRON STARS

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Abstract In this work, we delve into the key physical processes that govern magnetic fields and their evolution within neutron stars. Our investigation encompasses several crucial aspects: The fundamental properties of the matter constituting neutron stars. Understanding the extreme density, pressure, and composition of this matter is essential for accurately modeling the behavior of magnetic fields within them. Competing processes of the origin of powerful magnetic fields. We explore various hypotheses for how these fields may have formed during the birth of a neutron star or through subsequent processes. The limitations and mechanisms that influence the change of the magnetic field over time. This includes factors that may cause the field to weaken or strengthen over time, as well as potential instabilities that could play a role. A detailed analysis of the Hall drift. This specific phenomenon, where charged particles are separated due to a combination of their motion and the magnetic field, can significantly impact the evolution of the overall field.

Keywords: Evolution of magnetic field; magnetic field around neutron stars; Behavior and properties of evolution magnetic field; Collective motion driven by weak interactions in a matter; Movement of charged and neutral particles relative to each other; Hall drift;

I. INTRODUCTION

Our review dives into theoretical concepts about magnetic fields and their evolution in neutron star , especially how these fields might change over time. We won’t cover the basics here [1, 2] but will focus on the key ingredients that influence their evolution.

First, we’ll explore the properties of matter inside neutron stars, crucial for understanding how the magnetic field evolves. Next, we’ll briefly discuss how the field might have formed during the star’s earlier stages. Then, we’ll look at evidence suggesting the field changes over time and the equations that describe this process. Finally, we'll zoom in on one specific process, the Hall effect, presenting recent research and its implications

II. MATTER IN NEUTRON STARS

While protoneutron stars are born in a highly excited state with temperatures reaching $T \sim 10^{11}\,K \sim 10MeV$ (the same order of magnitude as the Fermi energies of their constituent particles), the rapid emission of neutrinos leads to a significant decrease in their internal temperature. Consequently, all neutron stars of known age that have been observed exceeding $\sim 10^3$ yr , are expected to possess internal temperatures at least 100 times lower. This translates to a state of high degeneracy, where the matter closely resembles its quantum ground state. However, minor deviations from this ideal ground state can introduce intriguing phenomena [3–5]. Notably, some of these deviations play a crucial role in the evolution of the magnetic field [6–8], which will be the focus of our subsequent discussion.

Within this state of high degeneracy, approaching thermodynamic equilibrium, the equation of state for the neutron star matter simplifies significantly. A single parameter, such as density or pressure, becomes sufficient to fully characterize the material properties. It's important to note that the density within a neutron star exhibits significant variation across several orders of magnitude. This range in density leads to distinct regimes with unique material properties, as will be covered in detail below. For a comprehensive exploration of this topic, refer to the seminal work by [9].

A. The outermost layer of a neutron star

The crust of a neutron star, where atomic nuclei reside, is designated as the crust. Similar to regular matter, these nuclei coexist with high-energy electrons that have too much energy because they are very dense, to form bound states with individual nuclei. At temperatures around $T \sim 10^{10}K$,the centers of atoms are expected to freeze into a solid structure, with only the electrons able to move freely.

In the past, the prevailing view was that The outermost layer was in its lowest possible energy state. This implies that at any given depth, a single type of nucleus, minimizing the local pressure enthalpy, dominates the composition, forming a highly ordered crystal lattice. However, Jones [4], challenged this view. They argued that thermodynamic fluctuations during the solidification process would lead to a multi-component composition at any given pressure, resulting in a significantly impure solid. This discovery could be very important for understanding how magnetic fields change over time, as it could significantly increase the resistance to electrical flow in the crust, especially at low temperatures [6].

As the density surpasses ”neutron drip” $\sim 4 \times 10^{11} gcm^{-3}$, free neutrons also emerge within the crust. Expected that, these neutrons to pair up and enter a superfluid state at a temperature similar to when the lattice freezes, essentially making them dynamically independent from the rest of the star. This idea has been suggested as a mechanism for pulsar glitches, sudden increases in a pulsar's rotation rate. Such glitches may arise from an abrupt shift in the angular momentum, transferred from the rapidly spinning superfluid neutrons. Despite the presence of these uncharged neutrons, their feeble interactions with electrons suggest that their influence on the magnetic field's development is likely negligible.

B. The central part of a neutron star

Beyond a density of approximately $\sim 2 \times 10^{14} gcm^{-3}$, which is lower than the typical density of atomic nuclei, individual nuclei are predicted to lose their distinct identities. This signifies a transition to a higher-density regime where matter becomes a fluid-like mixture of nucleons with electrons (n, p, e−). Mixture enriches with exotic particles like muons, hyperons, and mesons due to increasing in density.

Chemical equilibrium amongst this diverse particle population is established through weak interactions. Examples include neutron beta decay ($n \rightarrow p + e^- + \bar{\nu}$) and its inverse process ($p + e^- \rightarrow n + \nu$), in which neutrinos ($\nu$) or antineutrinos ($\bar{\nu}$) emitted hat can easily escape the star. During this phase, the Pauli exclusion principle strongly restricts available final states for interactions like electron-proton collisions, leading to exceptionally high electrical conductivity (as demonstrated by [10]). Notably, all particles within this dense medium possess some degree of mobility (with limitations to be addressed later), significantly complicating the analysis of magnetic field evolution.

Theoretical models suggest that strongly interacting particles during this phase (p, n, possibly hyperons) are forming (again) Cooper pairs and entering to a superfluid state. Here, the quantized neutron vorticity concentrates into microscopic vortex lines with a spacing significantly smaller than their average diameter. Similarly, the magnetic flux might be concentrated within analogous proton vortices. However, the transition temperatures required to reach these superfluid states remain highly uncertain.

Furthermore, the outermost layer of superfluids are unlikely to decouple as easily as the central part neutron super- fluid, effectively eliminating their role in pulsar glitches. Given the lack of compelling evidence for core superfluidity and the added complexity they introduce into already intricate magnetic field evolution models, we will primarily focus on scenarios that exclude them, although detailed discussions by other authors ([13, 14]) acknowledge their potential influence.

III. BEHAVIOUR AND PROPERTIES OF EVOLUTION

As discussed, the central part of a neutron star consists of several species of particles with a degree of mobility. Following the initial, transient period after a neutron star's formation, where all sound and Alfvén waves are damped out, the changes in the magnetic field are expected to happen gradually enough that the mass of the particles involved can be ignored. This allows us to employ the diffusion equation to describe the motion of each particle species (denoted by i) within the star,

$$0 = \nabla\mu_i - m_i^*\nabla\psi + q_i\left(\vec{E} + \frac{v_i}{c}\times\vec{B}\right) - \sum_j \gamma_{ij} n_j(\vec{v}_i - \vec{v}_j), \tag{1}$$

where $\mu_i$chemical potential (Fermi energy), m_i^* effective mass, $q_i$electric charge, $\vec{v}_i$ mean velocity, ψ is the gravitational potential, $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields, and the final term captures the momentum transfer due to collisions between different particle species j, each with number density n_j. The collisional coupling strengths are parameterized by the symmetric matrix γ_{ij}, whose coefficients generally depend on the location within the star.

The collision terms play two crucial roles in how the magnetic field changes over time:

a) Resistive Diffusion: Collisions can dampen the relative motion of positively and negatively charged particles. As a result, the magnetic field weakens and its influence becomes more widespread over time. However, the induced electric field within the highly conducting neutron star opposes this diffusion. For large-scale magnetic fields (comparable to the star's radius), the induced electric field dominates, resulting in minimal resistive effects over the lifespan of a neutron star (as shown by [10]). The influence of this diffusive process may be crucial solely in scenarios where the magnetic field is predominantly concentrated within a thin layer at the surface or if small-scale magnetic structures are created by other processes.

b) MHD Approximation: Collisions also tend to synchronize the velocities of different particle species, leading to a state where they move together on average. This behavior is captured by the standard Magnetohydrodynamic (MHD) approximation, which we will explore further in the following analysis.

If we sum the forces described by equation (1) across all particle species (' i') within a specific volume. This volume is chosen to have a total mass of unity and zero net electrical charge. By performing this summation, we arrive at the fundamental equation governing Magnetohydrodynamic (MHD) equilibrium.

$$0 = -\frac{\nabla P}{\rho c} - \nabla\psi + \frac{\vec{j} + \vec{B}}{\rho c} \tag{2}$$

where the mass density $\rho = \sum_i n_i m_i^*$, the current density $\vec{j} = \sum_i n_i q_i \vec{v}_i = (c/4\pi)\nabla \times \vec{B}$, and the pressure gradient term was obtained from the zero-temperature Gibbs-Duhem relation, $dP = \sum_i n_i d\mu_i$. we obtain taking the curl of eq. (2),

$$\frac{\nabla P + \nabla \rho}{\rho^2} = \nabla \times \left(\frac{\vec{j} + \vec{B}}{\rho c} \right) \tag{3}$$

We can see that the equation from right-hand side is not zero, then on the left-hand side the gradients of density and pressure cannot be parallel to each other in order for equilibrium to be achieved. However, in cold matter that has reached chemical equilibrium, this perfect alignment is unavoidable. Therefore, the existence of a magnetic field can be seen as a perturbation to this ideal state of chemical equilibrium. Due to slight misalignment between gradients of pressure and density the term of force on the right-hand become non-zero. The magnetic field within a neutron star relies heavily on this non-zero force term. Without this non-zero force, the dynamics of a neutron star's magnetic field would be significantly altered. A magnetic field with a horizontal curl component drives counterbalancing upward and downward fluid motions in different regions of the neutron star. This misalignment between the gradients and pressure acts like a brake on large-scale fluid motion. The only fluid motions that can happen relatively easily are horizontal motions driven by a magnetic force that curls purely in the vertical direction. This behavior reflects the stable stratification of neutron star matter (as described in [7, 15, 16]). This stratification is so strong that even the powerful magnetic fields of magnetars cannot overcome it and achieve significant vertical movement within the star. Only under specific circumstances, as outlined by, [7, 8] can this constraint be bypassed. There are two primary mechanisms that can circumvent the constraint imposed by the stable stratification and allow for vertical transport within a neutron star:

a) Elimination of Induced Chemical Imbalance: Weak interaction processes can eliminate the misalignment between pressure and density gradients caused by the magnetic field. This mechanism works best when the temperature is high, where these weak interactions occur more readily due to the increased thermal energy available.

b) Relative Motion of Particle Species: Under certain conditions, the different speeds of different types of particles within the fluid can also overcome the barrier caused by stratification.

A. Collective motion driven by weak interactions in a matter.

The Lorentz force, a consequence of the magnetic field, creates non-uniform pressure variations within the neutron star. The magnitude of these pressure perturbations can be estimated as$\delta P \sim B^2/8\pi \sim \sum n_i \delta\mu_i$. To understand this relationship better, let's consider the simplest possible scenario: a neutron star made up of just neutrons, protons, and electrons. We can further simplify by assuming there are always the same number of protons and electrons (charge neutrality). With this assumption, the total "chemical imbalance" $\Delta\mu$ can be estimated formed from the magnetic field strength B and the density of charged particles n_c:

$$\Delta\mu \equiv |\mu_p + \mu_e - \mu_n| \sim B^2/(8\pi n_c) \sim 3B_{15}^2 \text{ keV}. \tag{4}$$

where $B_{15} = B/10^{15}G$. The rates of the weak interaction an asymmetry has the effect of reducing this imbalance, Our assumption is that 'modified Urca reactions,' a specific type of energy transfer process, are the main contributor in this scenario. These reactions don't involve a phenomenon called 'Cooper pairing.' This assumption seems to match observations of how neutron stars cool down quickly in their early stages (as shown in Fig. 1 in Ref.11). It might also explain the later reheating process observed in rapidly spinning neutron stars called millisecond pulsars, where rotation plays a role alongside chemical reactions [3]. While $T \gg \Delta\mu$ [5], the imbalance decreases exponentially over time, with a decay constant of time $t_{\mathrm{mU}} \sim 0.5/T_9^6$ yr, estimates the time it takes for a neutron star to cool down significantly (represented by t_{mU}). The higher the star's temperature ($T = T_9 \times 10^9\mathrm{K} \approx T_9 \times 86\mathrm{keV}$), the shorter this cooling time. During this period, the effect of force of the Lorentz causes a small-scale displacement of the fluid $\sim \Delta\mu/\mu_e \sim 2 \times 10^{-5} B_{15}^2$ and to the radius.

$$t_{decay} \sim \frac{\mu_e}{\Delta\mu} t_{mU} \sim \frac{3 \times 10^{14}}{B_{15}^2 T_9^6}\ yr \tag{5}$$

the equation (5) estimates how long it takes for a strong magnetic field within a neutron star to weaken significantly (represented by t_{decay}). It considers factors like the number density of electrons (μ_e), the chemical imbalance ($\Delta\mu$), and the time of cooling the star (t_{mU}). An key point to consider is that for a very strong magnetic field and a hot star, however, it's important to point that this decay time is still much longer than the star's cooling time. This means the star could cool down significantly before the magnetic field weakens much, essentially "freezing" the field in place. The most natural source of energy to counteract cooling appears to be the magnetic field itself, as proposed by On the one hand, weak interactions can help release energy trapped within the magnetic field, potentially preventing it from becoming "frozen" due to the star's cooling. However, it's important to remember that weak interactions can also work against this goal. Without the presence of a chemical imbalance, these interactions can actually contribute to the star's cooling by causing the emission of neutrinos, which carry away energy. The heat released from the magnetic field can only counteract the star's cooling caused by weak interactions if there's a substantial chemical imbalance present. Specifically[3], suggest a threshold imbalance of $\Delta\mu \approx 5.5T$, which can be equivalently expressed as a magnetic field strength of $B_{15} \approx 13T_9^{1/2}$. A neutron star born with a strong magnetic field will initially be very hot. However, it will rapidly cool down until a specific condition is met. Once this threshold is reached, the star's temperature will stabilize around a value of $T_9 \sim 0.2[10^4 \text{ yr}/t]^{1/7}$. This stabilization is achieved through the injection of energy released by the gradual decay of the magnetic field itself. It's worth noting that calculation shows a value for this coefficient that's a bit bigger than what Thompson and Duncan found in their research, who pioneered this concept[17]. Additionally, the high temperature at this stable state suggests that the single-fluid Magnetohydrodynamics approximation remains a valid approach for modeling the star's behavior.

B. Movement of charged and neutral particles relative to each other.

The processes described above only applies to neutron stars with internal magnetic fields exceeding a critical value of roughly 5×10^{15} G. Stars with weaker magnetic fields wouldn't experience this significant decay or reheating before they reach a stage dominated by another cooling process called "photon-cooling" (described in [11]). For these stars, the only potential mechanism for magnetic field decay from the movement of charged particles relative to each other within the star.

To explore this possibility further, we propose a slight modification of the *npe* matter model developed by [8]. This model involves manipulating equations related to the diffusion of the three main particle species (neutrons, protons, and electrons) along with the magnetic field induction equation. By analyzing these combined equations (1), we aim to

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left[(\vec{v}_n + \vec{v}_H + \vec{v}_A) \times \vec{B}\right] - \nabla \times \frac{c\vec{j}}{\sigma} - \frac{2c}{e}\nabla\left(\frac{\gamma_{en} - \gamma_{pn}}{\gamma_{en} + \gamma_{pn}}\right) \times \nabla\left(\mu_p - \mu_e\right) \tag{6}$$

In situations where the final two terms (resistive and battery terms) are negligible (often the case in realistic conditions), the magnetic field can be seen as influenced by these three combined velocities:

a) the neutron velocity, neutron bulk motion carries the field along with the overall movement of the neutrons;

b) the Hall drift velocity, represents a separate relative movement of charged particles within the neutron star due to the magnetic field itself

$$\vec{v}_H \equiv \frac{\gamma_{en} - \gamma_{pn}}{\gamma_{en} + \gamma_{pn}}\left(\vec{v}_p + \vec{v}_e\right) = \frac{\gamma_{en} - \gamma_{pn}}{\gamma_{en} + \gamma_{pn}} \frac{\nabla \times \vec{B}}{4\pi n_c c} \tag{7}$$

c) the ambipolar diffusion velocity,

$$\vec{v}_A \equiv \frac{\gamma_{pn}\left(\vec{v}_p + \vec{v}_n\right) + \gamma_{en}(\vec{v}_e + \vec{v}_n)}{\gamma_{pn} + \gamma_{en}} = \frac{\vec{j} \times \vec{B}/(n_c \mathrm{c}) - \nabla(\Delta\mu)}{(n_n + n_c)\left(\gamma_{pn} + \gamma_{en}\right)} \tag{8}$$

describes the relative drift of charged particles relative to the neutrons, driven by the magnetic field but potentially limited by the distribution of chemical potential;

While weak interactions can theoretically eliminate the chemical imbalance caused by ambipolar diffusion, their timescales are similar to those of bulk motions. These processes can only work efficiently when it's very hot inside the star. High temperatures mean particles collide with each other often, which helps overcome a counteracting effect. Without enough collisions, ambipolar diffusion becomes too strong and slows things down too much. Here, collisions become less restrictive, but weak interactions are also much weaker. In this scenario, only a specific type of ambipolar diffusion (caused by a specific component of the Lorentz force [8]) can potentially operate (and even this is limited to a simplified case with specific assumptions).

Unlike ambipolar diffusion, Hall drift isn't affected by other forces within the fluid. Its speed depends only on the strength of the magnetic field itself. Inside the solid outer layer (crust) of the neutron star, where only electrons move freely, Hall drift and another process called resistive diffusion become the main ways the magnetic field can change. However, the situation within the fluid core is more complex. Here, the Hall effect interacts (or competes) with a highly restricted ambipolar diffusion, and this combined scenario remains largely unexplored (as referenced in [18]).

IV. HALL DRIFT

Within the solid, electrically conductive crust of a neutron star (or any similar medium), electrons are the sole mobile charges. Consequently, the equation known as the "Hall equation" govern the magnetic field's evolution in this environment

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left[\left(-\frac{c}{4\pi n_e e} \times \vec{B} \right) \times \vec{B} + \frac{c^2}{4\pi\sigma} \nabla \times \vec{B} \right] \tag{9}$$

There are two main terms on the right side of the equation: Hall drift: This term, represented by the first part with the curly brackets ($\nabla \times$...), describes how the magnetic field is influenced by the movement of electrons (the only freely moving charged particles in the crust) due to the Hall effect. Resistive diffusion: This term, represented by the second part with the curly brackets ($\nabla \times$...), describes another way the magnetic field can change due to the electrical resistance of the material [6, 19]

Scientists are still debating the relative importance of these two processes (Hall drift vs. resistive diffusion) in determining how the magnetic field evolves within the neutron star crust (as mentioned in references [20, 21]

Goldreich & Reisenegger [8] argued that the Hall effect dominates magnetic field evolution at large scales (comparable to the thickness of the crust). They drew an analogy to the Euler equation in fluid dynamics, suggesting that the non-linear term linked to the Hall effect could initiate a turbulent energy transfer process, cascading energy towards smaller scales within the crust. However, the existence of stable linear modes of stable linear modes would lead to a form of "weak turbulence." This type of turbulence exhibits an energy transfer timescale that generally exceeds the typical oscillation period at a particular scale. Consequently, the resulting power spectrum scales with wave number $\propto k^{-2}$. This differs slightly from the $\propto k^{-5/3}$ spectrum observed in Kolmogorov turbulence for fluids. Finally, Ohmic resistivity takes over at smaller scales, leading to the dissipation of magnetic energy.

Biskamp et al. [22] performed simulations to investigate the theorized turbulent cascade of magnetic energy because of non-linear Hall effect (similar to fluid dynamics). Surprisingly, their simulations revealed an energy cascade towards smaller scales, but with a steeper energy spectrum (proportional to $\propto k^{-7/3}$) than predicted ($\propto k^{-7/3}$).The steeper spectrum observed in the simulations suggests that the turbulence might be weaker than originally anticipated. This could be because of the presence of stable linear modes, leading to a longer energy transfer time compared to the oscillation period at each scale. This "weak turbulence" would result in a power spectrum $\propto k^{-2}$that deviates slightly from the standard Kolmogorov spectrum $\propto k^{-5/3}$ observed in fluid turbulence. Regardless of the specific turbulence behavior, at very small scales, ohmic resistivity ultimately takes over and dissipates the remaining magnetic energy.

An alternative approach involves exploring analytical solutions to the Hall equation, both with and without the resistive term. This approach has been pursued by

Vainshtein and [23], Cumming. [19], and research group [24, 25]. The work [23] considering a purely toroidal magnetic field, represented as $\vec{B} = \mathcal{B}(R, z, t)\nabla\phi$, where R, ϕ, z correspond to standard cylindrical coordinates. When this field evolves under the effect of the Hall equation, it retains its toroidal nature. To effectively describe this evolution, we introduce a new coordinate, denoted by $\chi \equiv c/[4\pi e n_e(R, z)R^2]$. Surfaces defined by constant values of χ (referred to as χ-surfaces) represent toroids located within the star. Additionally, a complementary coordinate, denoted by χ, can be expressed as each individual χ-surface. This complementary coordinate is expressed as $\partial/\partial s \equiv -R^2\nabla\phi \times \nabla\chi \cdot \nabla$. By employing this new coordinate system and neglecting the resistive term, the Hall equation transforms into the Burgers equation,

$$\frac{\partial\mathcal{B}}{\partial \mathrm{t}} + \mathcal{B}\frac{\partial\mathcal{B}}{\partial \mathrm{s}} = 0 \tag{10}$$

with implicit solution $\mathcal{B} = f(s - \mathcal{B}t)$. The strength of the magnetic field (represented $\mathcal{B}$) determines its movement. Each value travels along a designated surface defined by the variable χ with a speed proportional to its own strength. However, at specific points along this path, discontinuities (abrupt changes or breaks) can develop in the magnetic field. These points coincide with locations where the rate of change in the field strength (represented by $\partial\mathcal{B}/\partial s$) is significant.

In this simplified scenario, the resistive term becomes increasingly important and acts to smooth out the discontinuity. Consequently, magnetic energy dissipates at a relatively rapid rate as the Hall drift feeds it into the discontinuity. This process continues until, on the timescale characteristic of the Hall drift, the magnetic field $\mathcal{B}$ becomes uniform across each individual χ-surface. As a result, the remaining magnetic field, represented as $\vec{B} = \mathcal{B}(\chi)\nabla\phi$, only evolves on the much longer timescale associated with the resistive term (which is assumed to be significantly slower).

However, further studies by [25] revealed that this seemingly stable configuration is susceptible to small perturbations in the poloidal direction. These perturbations can grow over time because different segments of the poloidal field lines, traversing different χ-surfaces, experience varying speeds due to the Hall drift velocity induced by the toroidal field.

The key to understanding this might lie in conservation of magnetic helicity,

$$\frac{\partial}{\partial t}(\vec{A}\cdot\vec{B}) + \nabla\cdot(c\varphi\vec{B} + c\vec{E}\times\vec{A}) = -c\vec{E}\cdot\vec{B} \tag{11}$$

This equation (refer to equation number (11) for reference) derived from Maxwell's equations, sheds light on the importance of a concept called "magnetic helicity" (represented by $\vec{A}\cdot\vec{B}$). It shows that under specific conditions (zero electric field divergence and zero resistivity), the total amount of magnetic helicity within a volume is conserved. When there's no electrical resistance, the generalized Ohm's law simplifies to a specific form regardless of the motion of the fluid (represented by the velocity field $\vec{v}$). Studies by [26] suggest that stable configurations of MHD (magnetohydrodynamics) likely correspond to states with minimal energy for a given value of magnetic helicity. The Hall effect, another phenomenon in this context, also preserves the total amount of magnetic helicity.

The concept of magnetic helicity is particularly relevant here. Dimensionally, its density scales as $\sim B^2 L$, where B represents a characteristic magnetic field strength and L represents a characteristic length scale. In contrast, the magnetic energy density scales simply as$\sim B^2$. As a consequence, helicity tends to concentrate on larger scales within the system. This property makes it significantly more challenging to dissipate compared to magnetic energy. This observation suggests that configurations with strong helicity might achieve stability and resist decay through the processes discussed previously (excluding the exceptionally slow process of resistive diffusion). We are researching to find stable configurations with a high degree of helical symmetry

V. SUMMARY

Studying how magnetic fields evaluate in neutron stars is very difficult and we can learn a lot from observations and apply physics concepts. Interestingly, many of the same processes that affect magnetic field evolution in neutron stars are also seen in other systems, such as plasma physics labs and galaxies. By sharing insights between these different fields, we can improve our understanding of neutron stars and other systems. In this paper we focused on the physical mechanisms that influence the evolution of magnetic fields in neutron stars. Have been suggested that these magnetic fields likely originate during the hot, initial phase of a neutron star's life, following a supernova explosion. And the key factor was that stable stratification within the neutron star is emphasized as a crucial element for the long-term stability of the magnetic field. Explored the main properties of the matter found in neutron stars, potential scenarios for magnetic field generation, limitations and mechanisms affecting their evolution, and recent research on the Hall drift (a specific type of movement of charged particles within a magnetic field). Continued research into identifying stable, strongly helical magnetic field configurations is crucial, as these configurations could potentially remain stable under various processes, including resistive diffusion. The evolution of magnetic fields in neutron stars shares commonalities with processes observed in plasma physics laboratories and galaxies, emphasizing the importance of interdisciplinary insights for further advancements in the field.

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