Magnetic Fields of White Dwarfs and Neutron Stars

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Abstract

Neutron stars and white dwarfs are known to be the final stages in the life cycle of stars. These celestial objects are characterized by immense gravitational pressure, extremely high temperatures, and exceptionally high density. Additionally, some of them are known to possess extraordinarily strong magnetic fields under these extreme conditions. However, the precise mechanisms behind the generation of such strong magnetic fields remain unclear. The primitive virtual negative (PVN) charge dynamo mechanism proposed for solar planets in 2008, which involves the interaction between gravitational mass and electric charges, is applied to compact objects like white dwarfs and neutron stars because it is considered comprehensive and consistent.

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Introduction

Physics is one of the fundamental fields of study in physical science based on principles and laws; however, these principles and laws are not provable but assumed to be true based on empirical evidence from natural phenomena. This implies that physical science cannot be independent of natural philosophy.

According to the ontological interpretation for physical fields, such as electric, magnetic, and gravitational fields, they are representations in natural phenomena for the interactions with vacuum particles in 4-D complex space, from which physical interactions, such as gravitational and electromagnetic interactions, are interpretated as the spontaneous reactions of vacuum particles for equilibrium state in 4-D complex space, which is the first principle given in the space. Moreover, if the first principle is considered in 4-D complex space, physical mass is expected to interact with electric charges, in which primitive virtual negative (PVN) charge is defined for mass, and it can be a significant factor in macroscopic phenomena such as in astrophysics.

Astronomical bodies such as asteroids, moons, planets, and stars have been observed since the time humans appeared on Earth. Based on the data acquired from experiments and observations, theories are constructed to explain phenomena in the sky, with these theories ideally being applicable to astronomical bodies in general. Before we explore the astronomical bodies beyond our planet, it is important to first review the study of Earth--not far from us, but right beneath our feet.

Magnetic field of the Earth

Once upon a time, people believed that a permanent dipole magnet was embedded inside the Earth, which could explain the geomagnetic field, closely resembling a magnetic dipole at the Earth’s center. However, the idea of a permanent magnet was abandoned when it became clear that the temperatures inside the Earth are too high. As a result, researchers have since sought other sources of electric currents or activities within the Earth that could generate magnetic fields.

The anti-dynamo theorem states that an axisymmetric magnetic field cannot be maintained via dynamo action (Cowling, 1934). Although it is for a limiting ideal case in natural phenomena, it highlights the difficulty in achieving self-sustaining dynamo mechanisms, particularly for axisymmetric or nearly axisymmetric magnetic fields in astronomical bodies.

In contrast, the creationist free-decay theory was introduced, pointing that Earth’s magnetic dipole data since 1900 show evidence of gradual decay (Barnes, 1973; Humphreys, 2013). Furthermore, the feasibility of the dynamo theory, which is currently the most widely accepted explanation has also been called into question (HumphreysD, 2013; LandeauM., FournierA., NatafHC., Others, 2022).

In fact, new fundamental mechanism for the magnetic fields of Earth and solar planets, in general, was introduced (Kim, 2008). This unconventional yet groundbreaking theory proposed the existence of an intrinsic current source for axisymmetric magnetic fields, such as the dipole magnetic field of an astronomical body. According to this mechanism, the intrinsic current arises from the PVN charge of the body itself and its rotation. Therefore, irrespective of the constraints imposed by Cowling's anti-dynamo theorem, the axisymmetric magnetic field of the astronomical body can sustain itself. Moreover, astronomical bodies with magnetic fields are not isolated; rather, they are electrically connected to their environment.

The PVN charge dynamo mechanism can be described as follows: Consider a rotating protoplanet undergoing mass accretion from its surroundings. Due to its rotation, a current effect arises from the rotating PVN charge distribution associated with the protoplanet's mass, leading to the formation of an axially symmetric magnetic field.

As mass accretion continues, a differentiation process occurs in which heavier elements migrate toward the center, forming a high-density core. With increasing internal temperature, the core transitions to a liquid state composed of molten metallic iron-alloy or plasma. Within this environment, positive ions are attracted toward the core due to its PVN charge, while negative ions or electrons are pushed outward, resulting in electric charge separation driven by electrostatic interaction.

This separation of charges induces a positive charge distribution primarily in the outer core and a negative charge distribution in the outermost layer of the planet. These distributions, coupled with the planet's rotation, generate axially symmetric magnetic fields: one from the negative charge distribution in the outer layer and another from the positive charge distribution in the planet's inner layers. Consequently, two magnetic dipole moments are produced, with one embedded within the other, oriented in antiparallel directions.

As the mass accretion process continues, the planet's mass and volume increase, leading to a stronger magnetic field. The charge separation process within the planet persists until a force balance is achieved between the Lorentz force and the electrostatic force. This mechanism forms the basis of the PVN charge dynamo.

Naturally, the intensity of the magnetic field depends on the planet's mass, rotation period, and size. Accordingly, the magnetic dipole moment of a planet within the solar system can be expressed as:

$$\mathcal{M} \backsim C_{pvn} M R^{3} R_{ref}^{-1} T^{-1} \tag{1}$$

in which $C_{pvn} \sim 10^{-19}$ [C M^{-1}]; M is the mass; R is the radius; T is the rotation period of the planet; and R_{ref} is a parameter related to thermodynamic conditions and structural information of the planet.

Although we can expect a magnetic field on any rotating massive body due to the PVN charge of the body, the field is weak in general. However, for an astronomical body rotating with its PVN charge, the field strength is strong enough to act as a seed field for generating the main magnetic field, provided the astronomical body has a core and a hot plasma layer. In general, for any astronomical body, there are two necessary conditions to determine whether it has a magnetic field: rotation and the presence of a hot plasma layer in the core.

For solar planets, the magnetic dipole moments estimated using Eqn. (1) were compared with NASA data, where the estimations were slightly lower for planets with hard crusts and outermost shells, such as Mercury and Earth, and slightly higher for gas giants (Jupiter and Saturn) and ice giants (Uranus and Neptune). In these estimations, the parameter R_{ref} was set to 1 for convenience in estimating the order of magnitude (Kim, 2008).

For a gas giant (or ice giant) planet such as Jupiter, Saturn, Uranus, or Neptune, the main magnetic field is generated by positive charge distributions in the planet's outer core. This is because outcast electrons, which result from the process of charge separation, are in the planet's atmosphere; hence, they cannot contribute to generating the planet's main magnetic field due to the effects of Faraday's law of Induction and the high mobility of electrons. Therefore, it is expected that the directions of the magnetic fields in gas giants or ice giants point in the same direction, or somewhat close to the direction of their angular momentum, while terrestrial planets, such as Mercury and Earth, have magnetic fields that point in the opposite direction to their angular momentum.

Fig. (1) shows magnetic dipole moments estimated from observations[2] (solid blue circles) for solar planets, stars (Sun, 78 Virginis), and the Milky Way galaxy; magnetic dipole moments (empty red boxes) estimated using Eqn. (1), with $R_{ref} = 1$; and the ratios of observed values to their expected values based on Eqn. (1). Although there may be many factors influencing these ratios, such as chemical composition, internal temperature, and internal structure of planets and stars, the internal temperature may be a common criterion for determining how much electric charge a planet or star can hold. Additionally, the internal structure should be an important factor in a planet's or star's ability to retain electric charge.

For the ratio of Mercury $r{\sim}10^2$; Mars, $r{\sim}10^{-1}$;Venus, $r{\sim}10^0$; Earth, $r{\sim}10^1$; Uranus, $r{\sim}10^0$; Neptune, $r{\sim}10^0$; Saturn, $r{\sim}10^{-1}$; Jupiter, $r{\sim}10^{-1}$; Sun, $r{\sim}10^{-2}$; 78 Virginis, $r{\sim}10^{-1}$; Milky Way galaxy, $r{\sim}10^{-4}$.

Mercury is known as one of the iron-rich planets that is smaller and denser than other types of planets of comparable mass (Wiki-mercury, 2025), from which we can expect a field enhancement in the observation of magnetic fields. On the other hand, the temperature of Mars' core is estimated to be about 1500 K that is relatively lower than that of other planets such as Venus (5200 K), Earth (5700 K), and others. This suggests that Mars likely retains fewer electric charges compared to these planets.

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[2] The data consist of the contents from Table 1 in the works by Jacob Biemond. (Biemond, The Schuster-Wilson-Blackett Hypothesis, 2020)

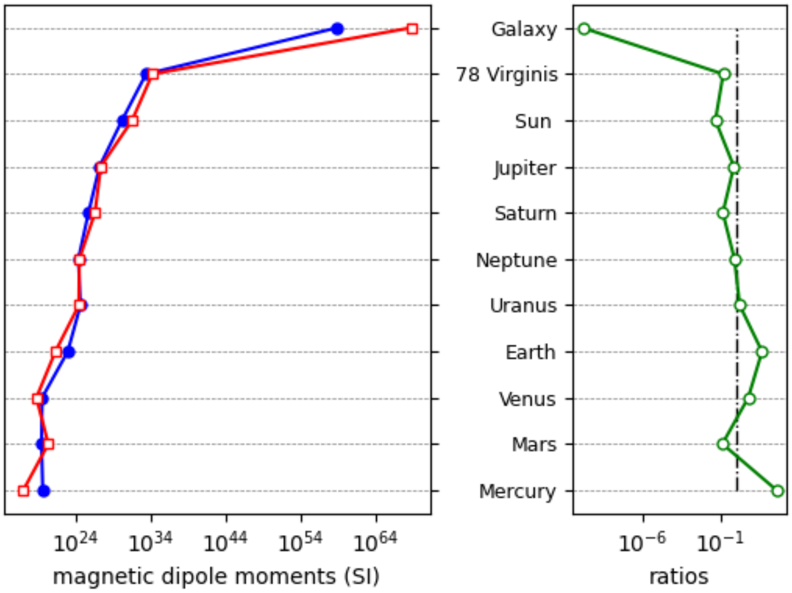

Figure 1: Magnetic Dipole Moments, Estimations, and Ratios (solar planets, etc.)

In contrast to terrestrial planets, Saturn and Jupiter are gas giant planets in which the main magnetic fields are generated by positive charge distributions in the outer cores and by the planet's rotations. Hence, the radius of the outer core is an important factor. This radius corresponds to the liquid metallic hydrogen layer with values of $r \sim 0.8\, r_J$ for Jupiter and $r \sim 0.5\, r_S$ for Saturn (Doug Kaupa Council BluffsIowa, 2025).

Next, the Sun is a star in our solar system radiating about 3.8×10^{26} watts of energy per second. The temperatures inside the Sun reach about 27 million K at the core and 9932 K at the outer layers (AI, Artificial intelligence). One possible reason for the ratio $r \sim 10^{-2}$ might be related to the high temperature inside the Sun, which prevents the electric charges from remaining as expected. Similarly, we can set $R_{ref} \sim 10^{2}$ for stars like the Sun.

It is interesting to note that the ratio $r \sim 10^{-4}$ in Milky Way galaxy might indicate that the magnetic dipole moment of an astronomical body is not simply related to its angular momentum. This suggests that there should be a dynamo mechanism linking the magnetic dipole moment to the angular momentum.

It is surprising that as early as 1923, researchers had already investigated the relationship between the angular momentum and the magnetic dipole moment of Earth (WilsonH., 1923). In 1947, this relationship was suggested in the form $P = \beta \cdot \sqrt{G}\; U\; c^{-1}$ (in CGS units) for a massive rotating body, a relationship later called the "Blackett effect" (S.Blackett, 1947). Here, P represents magnetic moment, G is the Gravitational constant, U is the angular momentum, c is the speed of light, and β is a dimensionless constant of the order of unity.

Similarly, this relationship was expressed as “magnetic Bode’s law”, which was, in fact, an empirical law since physical correlation of angular momentum to magnetic dipole moment for planets—i.e., the correlation between gravitation and electromagnetism had not yet been found in physics at that time (AhluwaliaD. & WuT., 1978; BaliunasSallie, SokoloffDmitry, SoonWille, 1996; ApellAgona, 2024).

Recently, further investigation has been conducted on the relationship between the magnetic dipole moment of a planet or celestial body—such as pulsars, white dwarfs, etc.—and its angular momentum (Biemond, The Schuster-Wilson-Blackett Hypothesis, 2020). It is agreed that there are two contributions to the magnetic field of a celestial body: one with a gravitational origin and the other with an electromagnetic origin, in which the gravitational contribution is much smaller in comparison. Now, we can apply the same dynamo mechanism resulting in Eqn. (1) for compact stars, white dwarfs and neutron stars. This mechanism uses the PVN charge of star itself to initiate a seed magnetic field. The main magnetic field of the star is then enhanced through further charge separation inside the rotating body of the star.

Since the primitive virtual negative (PVN) charge, which is generally defined for mass, interacts with electric charges, it is natural for any astronomical body to have an electric charge distribution induced by its PVN charge. If the astronomical body is rotating, it is expected to have a magnetic field. Furthermore, if the astronomical body has a hot plasma interior, the magnetic field is intensified through the dynamo mechanism. By the same token, its magnetic field is not independent of other astronomical bodies due to interactions between their PVN charges and electric charges inside the astronomical body.

In addressing questions about why and how solar cycle occurs, a possible explanation was sought by comparing the variations of sunspot numbers and interaction strength with the solar planets (Kim, 2020). The electric charge distribution inside the Sun should be affected by interactions with the planets of the solar system, which revolve around the Sun. The strength of these interactions is periodic, with Jupiter and Saturn being the most dominant among the eight planets. Interestingly, the conjunction period of Jupiter and Saturn is approximately 20 years.

The idea behind the comparison was as follows: when the planets Jupiter and Saturn line up with the Sun on one side and the other planets on the opposite side, the interaction strength with the Sun is at its maximum, causing the interaction to be intensified in one direction. Conversely, if these two planets line up with the Sun in the middle, the interaction strength is at its minimum, causing the interaction to split the charge distribution in both directions. If the interaction is strong, positive charges are pulled out of the Sun’s core and move toward the convection zone, with positive charges accumulating in the convection zone as the Sun rotates; if the interaction is weak, the positive charges retreat back to the core, and negative charges accumulate in the convection zone.

White Dwarf

In a star’s life cycle, a white dwarf is one of the final stages, along with other compact objects such as neutron stars and black holes. These final stages are categorized based on the star’s mass.

According to artificial intelligence (AI) on the internet, a white dwarf is the stellar core left behind after a star has used up its nuclear fuel and shed its outer layers. Hence, it can be called a star remnant or a compact star, with extremely high mass density, in which no further nuclear fusion occurs. It is composed mainly of carbon (C) and oxygen (O) in the core, with helium (He) and hydrogen (H) in the outer shells. It is known that all nuclei exist in an ionic plasma state with a degenerate electron gas.

Due to the PVN charges of a white dwarf, an equal amount of negative charges, primarily electrons, are pushed beneath the crust (outer shell), while the positive charges behind are rearranged to neutralize the interior. Nevertheless, there may still be an excess of positive charge distribution. If the white dwarf is rotating, the negative charge distribution beneath the crust is expected to generate the major magnetic field of the white dwarf. The process of charge separation continues between the interior and beneath the crust through Lorentz force. It is known that a white dwarf has a hard crust and an internal crystalline nucleus structure with degenerate electrons, existing in a completely ionized, isothermal plasma state. The distribution of positive charges moves to the center of rotation, while electrons move outward beneath the crust. The magnetic field of the white dwarf increases until a force balance is reached, with electrostatic and Lorentz forces under the thermodynamic conditions inside the white dwarf.

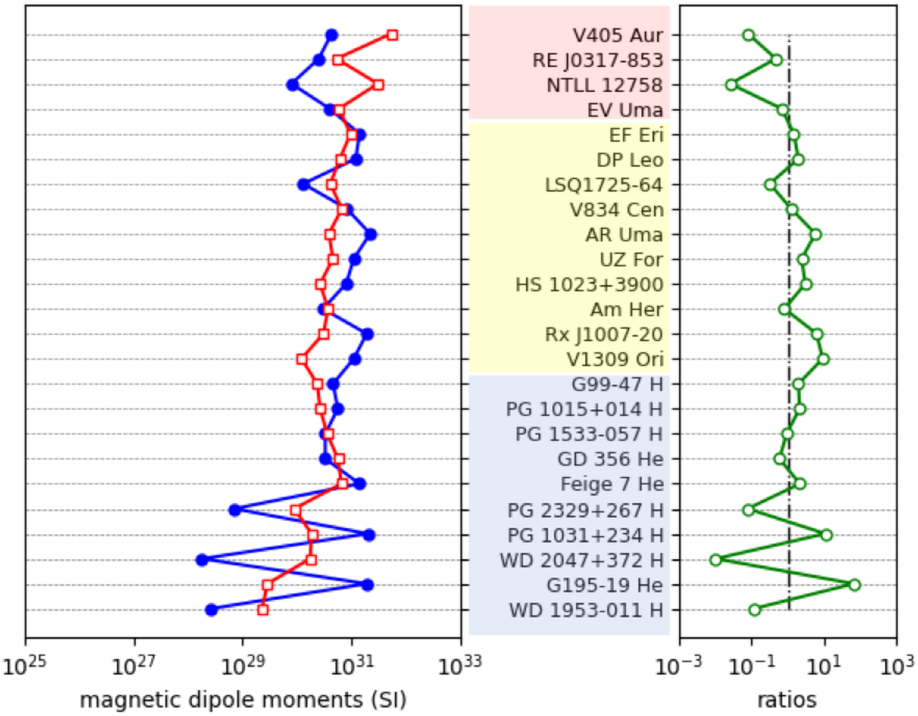

Figure 2: White Dwarfs ($R_{ref} = 1.756 \times 10^{-3}$)

Fig. (2) shows magnetic dipole moments (blue circles) of isolated magnetic white dwarfs (names in blue box), AM Herculis white dwarfs (names in yellow box), and asynchronously rotating white dwarfs in binaries (names in red box). The data for the magnetic dipole moments are taken from the work of Jacob Biemond (BiemondJacob, 2020). The figure also represents estimations using Eqn. (1) (red boxes), where $R_{ref} = 1.756 \times 10^{-3}$, and the ratios of the magnetic dipole moments to the estimations (green circles). The R_{ref} values evaluated from Eqn. (1) follow a log-normal distribution, meaning that $\log(R_{ref})$ values show a normal distribution. The possible reason for the log-normal distribution of R_{ref} values appears to be the uncertainties in the data and their propagations. Python software programs were used for the data fitting process.

Fig. (3) shows the log-normal distribution of R_{ref} values and the normal distribution of $\log_{10}(R_{ref})$, from which $R_{ref} = 1.756 \times 10^{-3}$ (10^{μ}).

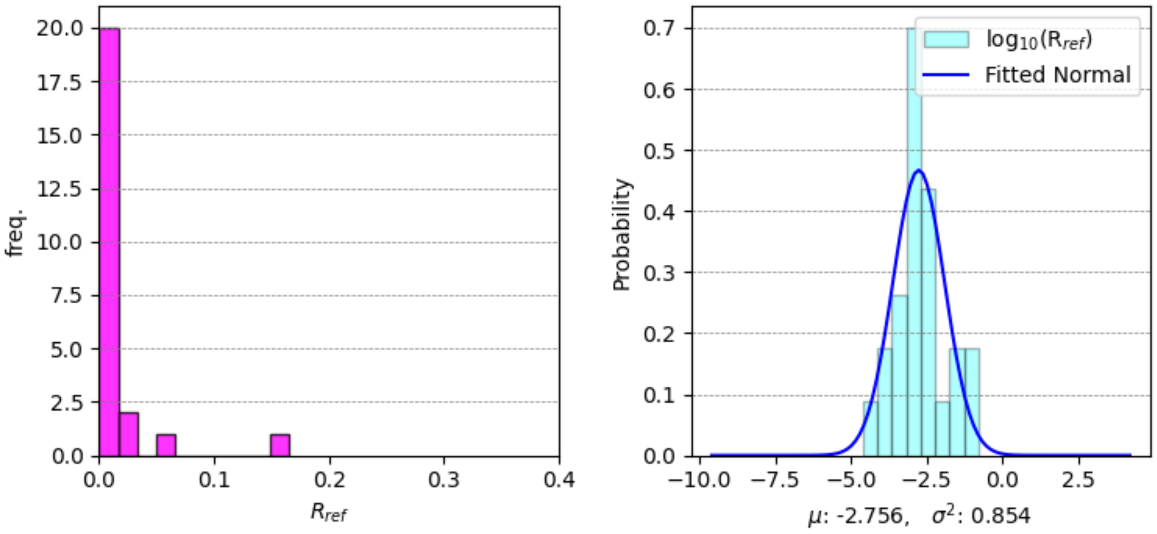

Figure 3: log-normal distribution of R_{ref} data and normal distribution of $log_{10}(R_{ref})$

If the magnetic field of an astronomical body has a magnetic dipole structure, the magnetic field induction B can be expressed as:

$$B_p = \frac{\mu_o}{4\pi} \frac{2\mathcal{M}}{R^3} \quad \text{(SI units)}, \tag{2}$$

in which $\mathcal{M}$ is magnetic dipole moment, R is the radius of the body, B_p is the magnetic field induction at the north pole of the body. The magnetic dipole moment of the body is then given by $\mathcal{M} = FB_pR^3$, where $F = 2\pi/\mu_o = 5 \times 10^6$. In Eqn. (1) the R_{ref} is expressed as:

$$R_{ref} \sim \left(\frac{C_{pvn}}{F}\right) \frac{M}{B_p T}, \tag{3}$$

where $C_{pvn} = 10^{-19}$; M is the mass, T (in seconds) is the period of rotation. If the mass and the period have been known for an astronomical body, the magnetic field induction of the body can be estimated as $B_p \sim 2 \times 10^{-26} \cdot MT^{-1}R_{ref}^{-1}$, in which R_{ref} is given for stars in the same category.

In Appendix A, the mass of white dwarf stars is compared to its estimation from Eqn. (3). As shown in Fig. (5), the distribution of $\log_{10}(M/M_{est})$ shows a normal distribution, and the mean value μ close to zero, where $R_{ref} = 1.756 \times 10^{-3}$.

Neutron Star

Scientific papers, archives, websites, and other sources do not clearly explain the mechanism behind the strong magnetic fields of neutron stars. It is known that the magnetic flux of a star is conserved during the core collapse following a supernova explosion; however, we must first understand the origin of the magnetic field and how it is preserved during the collapse.

Nuclear processes such as nuclear fission and nuclear fusion are natural phenomena that help nuclei become more stable. It is known that inside a star, where nuclear fusion occurs, the fusion process will cease if an external force or energy—sufficient to overcome the threshold energy for fusion—is not supplied. Otherwise, the process continues until the nucleus becomes the iron nucleus that is known as the most stable nucleus in nature. If, however, an external force or thermal energy inside a star is enough to break apart the iron nucleus, what might happen next?

In nuclear physics, we know that the nucleus consists of both protons and neutrons, not just protons. This is because the electric repulsive interaction between protons can be overcome by the presence of neutrons, which also allow the nucleus to remain stable. Similarly, as long as each nucleon retains its identity, it can be expected that nucleons (protons and neutrons) will reorganize themselves to minimize the repulsive interactions among them.

On the other hand, atomic nuclei can also be explained by spin-spin magnetic interactions between nuclei, as described by the NP magnetic pairing model (Kim, 2022). Similarly, we can hypothesize that superheavy nuclei, under enormous gravitational pressure, might be more feasible and stable than individual neutrons packed inside the collapsed core. If the superheavy nuclei in the core are fermions, the distribution of these nuclei and electrons would prevent further collapse.

We can suggest an alternative, yet feasible, model as follows: under enormous gravitational pressure, the collapsed core is composed of superheavy nuclei in a plasma state, with electrons pushed to the outermost layer of the core due to the core's PVN charge. The magnetic field of the so-called neutron stars is generated by the electron distribution in the outermost layer and by the rotation, which is enhanced by angular momentum conservation. The superheavy nucleus consists of protons and neutrons, but the ratio of neutrons to protons is much greater than 1, as expected in nuclear physics, where some protons are converted into neutrons through weak interactions.

In the process of core collapse, as gravitational pressure increases, electrons, due to their high mobility and core's PVN charge, move to the outermost layer. Some of these electrons participate in weak interactions, which result in the conversion of protons into neutrons. As the collapse continues, the core's rotation increases due to the conservation of angular momentum, causing the core’s magnetic field to intensify. More electrons move to the outermost layer, and the positive charge in the outer core increases.

Under extremely high pressure and temperature, nuclei in the core begin to disintegrate into nucleons (protons and neutrons), and superheavy nuclei may form. If the positive charge density becomes too high to maintain the balance between electrostatic and Lorentz forces within the core, electrostatic discharges occur. Through these discharges, some protons in the core may be converted into neutrons via weak interactions, or hydrogen atoms may form in the outermost layer, causing the core’s magnetic field to decrease and its rotation to increase. In addition to the conservation of angular momentum, the homopolar-motor effect—caused by electrostatic discharges in the core—can also help explain the rapid rotation observed in some neutron stars.

However, in the core’s magnetic field, the decrease in the magnetic field by the net electric charge loss is much bigger than the increase from the rotational speed increase caused by the homopolar-motor effect, when considering the motor efficiency in the core where electrical discharges are occurring.

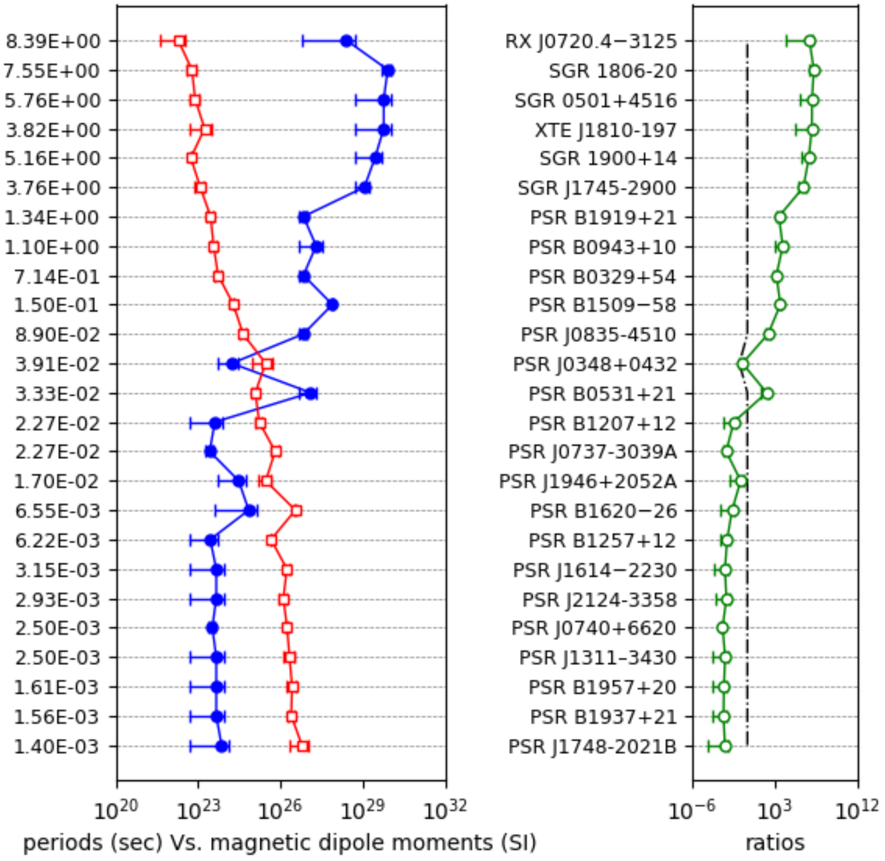

Figure 4: Neutron Stars (including millisecond pulsars and magnetars)

Fig. (4) shows magnetic dipole moments[3] of neutron stars and their periods (not to scale). Solid blue circles represent expectations evaluated from data[4], while red empty boxes show estimations with Eqn. (1), in which $R_{ref} = 1$. Green circles display the ratio of expectations to estimations. In Fig. (4), each data point for magnetic dipole moments and ratios is represented with upper and low limits indicated by bars.

As shown in Fig. (4), the magnetic dipole moments of neutron stars exhibit significant differences between those with periods of a few seconds and those with milliseconds periods. This suggests that if electrostatic discharges occur between positive charges in the outer core and negative charges (electrons) in the outermost layer during the formation of the neutron star, especially during core collapse, the core loses electric charges even though its spin increases to a certain degree. This results in the differences in magnetic dipole moments.

The reference values of R_{ref} in Eqn. (1) for neutron stars are divided into two subcategories: $R_{ref} \sim 10^{-7}$ to 10^{-8} for relatively slow rotating neutron stars (magnetars), and $R_{ref} \sim 10^{2}$ to 10^{3} for fast rotating neutron stars (pulsars). This implies that the formation history of the neutron star must be considered for R_{ref}, along with the thermodynamic conditions and the structural information within the star.

It is known that the mass and the radius of neutron stars have ranges as $1.2\ M_{\odot} \leq M \leq 2.1 M_{\odot}$ and $R \sim 10\ \mathrm{km} - 12\ \mathrm{km}$, respectively. In contrast, the typical mass of white dwarf stars is around $0.5\ M_{\odot}$ and the radius is around $0.01\ R_{\odot}$, which is about the size of Earth. To estimate the order of reference value R_{ref}, we use the correlation as $R_{ref} \sim 2 \times 10^{-26} \cdot M B_p^{-1} T^{-1}$. From these correlations among mass M, period T, and magnetic field induction B_p, one can estimate any of these variables if the other two are known.

The mass range for neutron stars is known to be narrow, spanning from 1.1 to 2.3 solar mass $M_{\odot}$, with an average mass ranging from 1.4 to $2\ M_{\odot}$. If the period T and magnetic field B of a neutron star are known, we can estimate its mass using the following equation:

$$M \sim 5 \times 10^{25} \cdot R_{ref}\, B_p T \ \ \text{(SI units)}.$$

Using this equation, we can estimate the R_{ref} values for magnetars and millisecond pulsars.
For example, the mass distribution for magnetars can be reviewed using data from the McGill Online Magnetar Catalogue (McGill Pulsar Group, 2020). Although the distribution follows a log-normal shape due to uncertainties, the mean value μ in a normal distribution of $\log_{10}(M)$ should represent the average mass of magnetars. This data shows that the average mass $\langle M \rangle \sim 1.4\ M_{\odot}$ when $R_{ref} = 6 \times 10^{-7}$.

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[3] In general, the magnetic fields of stars are believed to have a dipole structure.

[4] Data: mass, radius, spin, and B-field of neutron stars are acquired through web searching and using AIs (Artificial intelligence, AI).

Another example is the mass distribution of magnetars from data[5] provided by Australia Telescope National Facility (Manchester, 2005), shown in Appendix B, where $R_{ref} = 3.7 \times 10^{-6}$. Similarly, the mass distribution of millisecond pulsars, reviewed with data from pulsars having rotational period is less than 0.01 seconds, shows that the average mass of millisecond pulsars $\langle M \rangle \sim 1.4\ M_{\odot}$ when $R_{ref} = 3.3 \times 10^{2}$. These estimated values of R_{ref} for magnetars and millisecond pulsars are consistent, in terms of order of magnitude, with the estimations from the data shown in Fig. (4).

Discussion

If there is a magnetic field, there must be electric currents or at least moving electric charges to produce it. Therefore, for the Earth's geomagnetic field, there must be electric currents within the Earth, something that everybody can agree on. As of today, geodynamo theories do not appear to be sufficiently robust as a general theory applicable to the dynamo mechanism in astronomical bodies. Researchers use computer simulations to study physical processes that cannot be directly confirmed through experiments. However, while simulation results can serve as references, they cannot be considered definitive evidence for any corresponding theory, especially when many adjustable parameters and initial conditions are involved. Simulation outcomes can vary significantly, much like the butterfly effect in weather forecast models.

More than a hundred years ago, scientists investigated the relationship between the Earth's angular momentum and its magnetic dipole moment. Although this relationship has not been fully explained by physics, the investigation has since expanded to include all astronomical objects, including white dwarf stars and neutron stars. Here, we can explain the connection between the angular momentum and magnetic dipole moments of white dwarf stars, neutron stars, and possibly other astronomical objects, through the PVN charge dynamo mechanism.

In an old-school memory, a teacher once remarked that real physics is born from discussions in a coffee room rather than from sitting at a desk with a pen and paper. It is important to remind ourselves of Occam's Razor: the mechanism of magnetic fields in astronomical objects such as stars, planets, etc., should be simple and unique.

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[5] ATNF: https://www.atnf.csiro.au/research/pulsar/psrcat/

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Appendix A - Mass distribution of white dwarf stars

For white dwarf stars, the reference value $R_{ref} = 1.756 \times 10^{-3}$, which is evaluated using Eqn. (1) or Eqn. (3) with data given by Jacob Biemond (Biemond, Magnetic White Dwarfs and Gravitomagnetism, 2020). Then, mass distribution estimated with Eqn. (3) and the R_{ref} is compared with mass in the data.

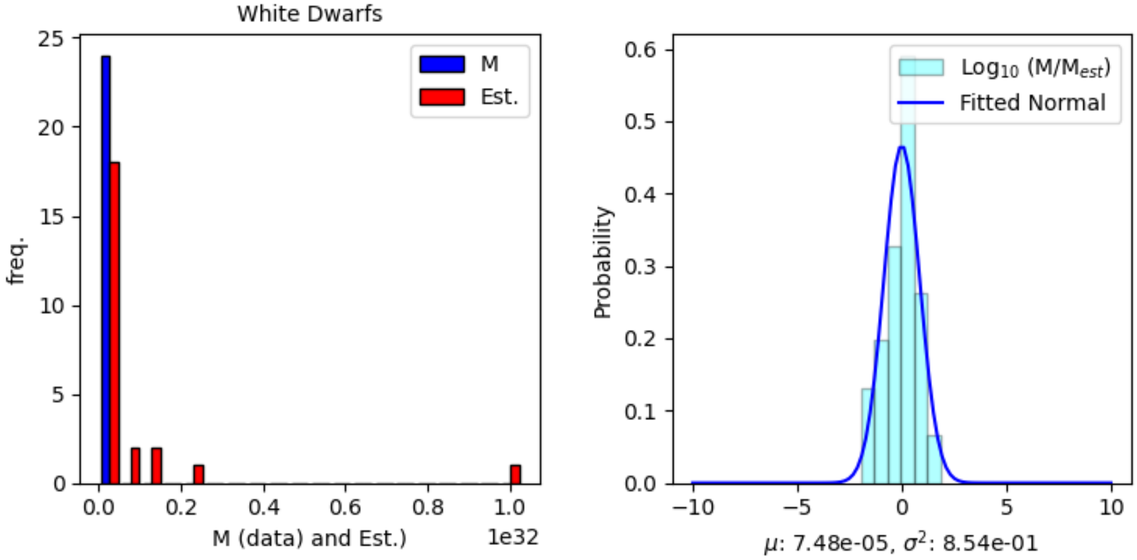

Figure 5: comparison of mass distributions from data and estimations

As shown in Fig. (5) the estimated mass distribution shows an unrealistic tail, which is probably came from propagation of uncertainties in the data, such as period T, magnetic field B_p, mass M in SI units. However, the distribution of $\log_{10}(M/M_{est})$ shows a normal distribution, and the mean value μ closes to zero in the distribution.

Appendix B

Mass distribution of magnetars

In the ATNF Pulsar Catalogue (Manchester, 2005), retrieval data includes pulsar information such as Name, rotation period (p0), and B-field (BSURF), in which pulsar records include magnetars and millisecond pulsars. Since magnetars is known to be categorized with such strong B-field strength ($10^{13} G$ to $10^{15} G$), 103 records are selected out of 2752 for magnetars. Fig. (6) shows the average mass of magnetars $\langle M \rangle \sim 1.4\ M_{\odot}$, in which $R_{ref} = 3.7 \times 10^{-6}$.

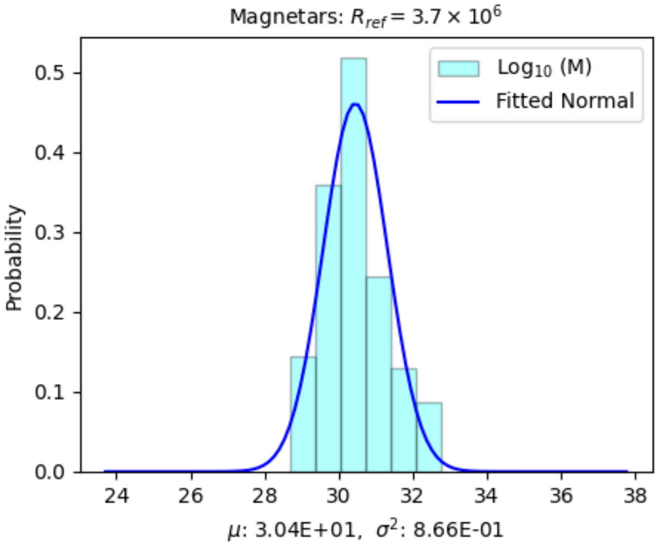

Figure 6: magnetars ($B \geq 10^{13}\ G$)

Mass distribution of millisecond pulsars

The rotational period T of millisecond pulsars is known as $T < 10\ ms$. 329 records are selected in the retrieved data. Fig. (7) shows the average mass of magnetars $\langle M \rangle \sim 1.4\ M_{\odot}$, in which $R_{ref} = 3.3 \times 10^2$.

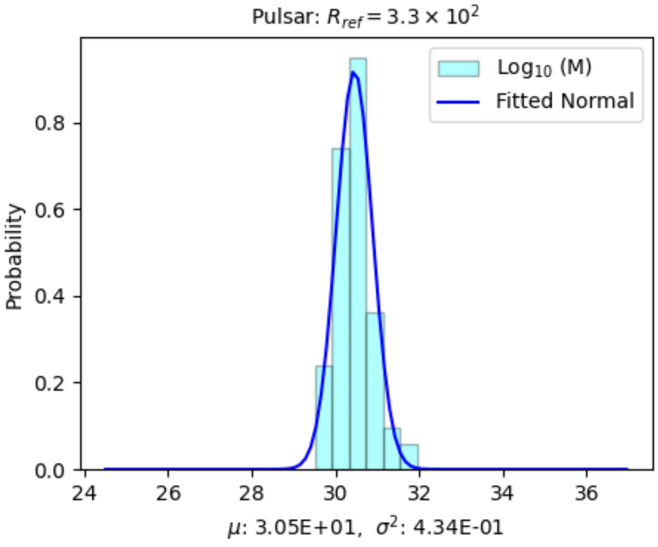

Figure 7: millisecond pulsars