AXISYMMETRY AND DYNAMO MECHANISMS IN SATURN'S INTERNAL MAGNETIC FIELD: CHALLENGES, THEORIES, AND FUTURE PROSPECTS

Abstract

Saturn's magnetic field, characterized by its near-perfect axisymmetry of the dipole axis, presents a unique and enigmatic phenomenon not observed in other planets with active dynamos. The prevailing theoretical explanation for the high axisymmetry of Saturn's magnetic field is attributed to the downward separation of helium from hydrogen, as proposed by Stevenson. Numerous studies have supported Stevenson's theories, but there are also dissenting opinions. Further research is needed to have a deeper understanding of the mechanism of producing an axisymmetric internal magnetic field. Since accurate rotational data, atmospheric helium mass fraction, and flow-induced gravity signals are imperative for accurate modeling of Saturn’s magnetic field future missions to Saturn should focus on the measurement or collection of data from various angles and locations around Saturn. Additionally, the possibility of a secondary dynamo action due to deep zonal flow and small-scale convective motion in the semiconducting region should be explored. Also, synthesizing improved numerical modeling methods and computational power will contribute to a better understanding of its internal magnetic field.

Keywords: Saturn's internal magnetic field, axisymmetry, Models of magnetic field, dynamo theory, Stevenson’s model, Cowling’s Theorem

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I. INTRODUCTION

Saturn's magnetic field was expected to be mainly a dipole, with a moderate tilt from its rotation axis and surface field strength between that of Earth and Jupiter. However, when the first measurement of Saturn's magnetic field was made by the Pioneer 11(P11) spacecraft in 1979 andanalytical models were developed the field was found to be weaker than expected by about three to five times. More peculiarlythe field had a high level of symmetry around the rotation axis with polarity opposite to that of the Earth. Subsequently, measurements were also made by Voyager 1 (V1), and Voyager 2 (V2) spacecraft, and more models were developed based on these voyagers' dataset. All these models gave the same general picture of Saturn's intrinsic magnetic field.It was almost perfectly axisymmetric, dipole dominant with north-south asymmetry, and the magnetic equator was offset to the north [1- 4]. Cassini, which orbited Saturn from 2004 to 2017, confirmed the nature of Saturn's internal magnetic field, as revealed by previous flybys [5, 6].

The almost perfect alignment of Saturn'smagnetic dipole axis and its rotational axis is a unique characteristic among known planetary dynamos asit has not been observed in any other planet with an active dynamo. The only other planet that may have a similarly aligned dipole is Mercury.This unique and puzzling feature of Saturn's magnetic field suggests that a different mechanism or dynamo action must be at work within Saturn's interior [7**].**It is a challenge to dynamo theory, but it also provides an opportunity to learn more about the interior of Saturn and the mechanisms that generate planetary magnetic fields. According to Stevenson (1980, 1982), the operation of the dynamo beneath stably stratified electrically conductive layers, formed by the precipitation of helium, can account for both the low dipole moment and the pronounced axisymmetry observed in Saturn's magnetic field [2].Numerous studies [1, 7, 9-12] have lent support to Stevenson's theories; however, there are dissenting opinions as well [4, 11] highlighting the complexity of the field.

Given that planetary magnetic fields are sustained by the Dynamo process, analyzing factors such as field Strength, spatial configuration, power spectrum, and temporal fluctuations can unveil the dynamo region's depth, as well as the planet's interior composition, structure, and dynamical conditions [2, 12]. Furthermore, magnetic field models can facilitate the examination of charged particle transportation, energization, loss, and interaction with rings and satellites within Saturn's inner magnetosphere.

This paper delves into the intricate nature of Saturn's internal magnetic field, assessing existing theories, identifying their limitations, and proposing avenues for further research to achieve a complete understanding of this unique feature. That is to have a comprehensive understanding of the Axisymmetrization of Saturn's magnetic field. Also, it is meant to help the reader get a better understanding of the dynamo theory and the generation of magnetic fields in Saturn.

II. AXISYMMETRIZATION OF SATURN'S MAGNETIC FIELD

Model-based on the high-field fluxgate magnetometer (FGM) data by the P11 showed that the magnetic field was tilted by about 2° ± 1° from the rotational axis and that the axis was offset by 0.04 - 0.05 Saturn radii (Rs=60,628km) in a northward direction. [13-15]. Conversely, the P11 Vector Helium Magnetometer (VHM) data reveal a tilt magnitude of less than 1° and an offset along the polar axis equivalent to 0.04±0.02 Rs[16, 17]. Subsequent measurements by the V1 in 1980 and V2 in1981 confirmed these findings. The Voyagers measurements also showed that the dipole moment of Saturn's magnetic field was about 0.21 ± 0.005 Gauss (G) which is about one-tenth the strength of the Earth's magnetic field and the magnetic axis tilted at 0.7° ± 0.35° [1,17-19] .

As per the Cassini spacecraft which made the most detailed measurements of Saturn's magnetic field to date the dipole tilt is smaller than 0.007° (approximately within 0.06° or 25.2 arc seconds)[10,3].

The almost perfect axisymmetric nature of Saturn's internal magnetic field poses challenges for dynamo theory for several reasons:

1. According to Cowling's Theorem, it is impossible for an active magnetohydrodynamic (MHD) dynamo process to produce a completely symmetrical magnetic field. This is because an MHD dynamo relies on a net movement of the fluid along the axis of rotation, which is lacking in a perfectly symmetrical field.

   Cowling's Theorem pertains specifically to the magnetic field within the region where the dynamo operates, which in this case, is the core of Saturn. But, the axisymmetric magnetic field observed is located outside the planet. Therefore, if there is a mechanism capable of converting a non-symmetrical field generated within Saturn's dynamo region into an axisymmetric field beyond the planet, it would not violate Cowling's Theorem.[3].
2. Numerical simulations of dynamos have not encountered such behaviour.
3. None of the other planets with active dynamos have nearly perfectly aligned dipoles, except possibly Mercury.
4. It makes determining the rotation rate of Saturn's deep interior accurately difficult [22, 23].
5. Challenges the understanding of MHD dynamo processes.

III.DYNAMO ACTION INSIDE SATURN

Saturn has a core that makes up about a quarter (25%) of its mass and a seventh (15%) of its radius. The core is wrapped in a fluid layer of hydrogen and helium, which is covered by another fluid layer of the same elements in molecular form [24, 25, and 17].

The core's properties depend on how fast it rotates, how much helium is in the atmosphere, how gravity is affected by the flow, and how hydrogen and helium behave under pressure [26].The core also produces the planet's magnetic field through a dynamo process. The core is thought to be small because the magnetic field is not very distorted [16, 27]. The dynamo is driven by factors such as hydrogen becoming metallic, helium separating from hydrogen, and different layers forming in the hydrogen-helium region [28].

Under high pressure and temperature, hydrogen changes into a state called metallic hydrogen or Coulombplasma, where it can conduct electricity. This happens at pressures around 2 million bars and temperatures below or equal to 10,000 K. Recent studies show that the pressure needed for this change is 190 GPa at 3000 K, and 300 GPaat 400 K and 0K [29, 30-32].

Based on both theoretical predictions and experimental evidence, hydrogen undergoes a transition from a molecular state to a metallic state at pressures of approximately 140-200 gigapascals (GPa). This pressure range corresponds to a depth roughly equivalent to half of Saturn's radius (Rs), which is approximately 60,000 kilometers (Rs = 60,000 km) [32, 33]. At this point, helium does not mix with metallic hydrogen anymore and forms raindrops [9, 1, 2, and 33]. These raindrops may fall all the way to Saturn’s rocky core[9, 17, 34].Moreover, in the deeper parts of the planet where pressure is higher, helium can mix with metallic hydrogen again and cause convection and dynamo activity[35,17].

Helium depletion in the molecular envelope releases an estimated energy of about1.7 x 10^{12} to 2.5 x 10^{12} ergs per gram of helium removed. This energy release, occurring during the transition from an initial mass fraction of 25% to 15% helium, can sustain the excess heat output for approximately 2 x 10^{9} years [36, 75, 13].

As hydrogen transitions into a metallic state, it becomes an electrically conductive fluid. The minimum conductivity of a metal is achieved at 140 GPa, with a density nine times that of initial liquid H_2 and a temperature of 2600 K. Even at pressures slightly lower than the transition to a metallic state, hydrogen can act as an effective semiconductor. In this region, high velocities can generate sufficient conductivity to support dynamo action. The transition from a semiconductor to a metallic fluid occurs at a pressure of 1.4 Mbar, which corresponds to approximately 0.63 times the radius of Saturn [37-39].The electrical conductivity of Saturn's interior gradually increases with depth. While conductivity is negligible near the surface, it sharply rises within the Mbar pressure range due to hydrogen ionization. As conductivity increases with depth, so does dynamo activity [2,3,39-44].The estimated electrical conductivity of liquid metallic hydrogen suggests that dynamo action likely occurs at shallower depths than experimental values indicate [44,45].

IV. STEVENSON’S (1980,1982) model

Stevenson proposed a mechanism to elucidate the process of axisymmetrization, which hinges on the interplay of differential rotation, particularly zonal flow, within the electrically conductive layer above the profound dynamo source region. This differential rotation functions akin to an electromagnetic filter or dampener, effectively suppressing any non-axisymmetric facets of the magnetic field. As a consequence, beyond the dynamo zone, an axisymmetric magnetic field is generated, aligning with the observations made in regions outside the planet [1, 7, 9-11].

At pressures of approximately 2 Mbar and temperatures hovering around 10^{4} K, hydrogen undergoes a transition into metallic hydrogen, leading to the formation of a Coulomb plasma where protons are encircled by an almost uniformly distributed degenerate electron sea [46].This transition engenders limited mixing of helium with metallic hydrogen, leading to the phenomenon known as "helium rain" [31]. As helium segregates from the hydrogen-helium amalgam, helium droplets, reaching sizes of roughly 1 cm, gravitate due to gravity, depleting the upper layer and augmenting the lower strata [47-49]. During this process, energy is released through minute-scale viscous dissipation. The miscibility of helium is contingent upon the temperature, indicating that phase separation might primarily occur in the upper part of the metallic hydrogen zone, with helium likely dissolving and intermixing at greater depths where temperatures are higher [26].

This results in the formation of a compositional gradient-stable stratified layer at the upper boundary of the metallic conductive region. The molecular envelope, linked convectively to the phase separation domain, gradually becomes helium-depleted. This three-tier structure in the hydrogen-helium domain encompasses an intermediary layer characterized by pronounced stability against substantial vertical movements owing to the presence of a helium gradient.

Within this stable stratum, thermal winds emerge, originating either from temperature discrepanciesbetween the equator and the poles or from intrinsic convection patterns within Saturn's molecular atmosphere. These thermal winds contribute to the axisymmetrization of the magnetic field by filtering out any non-axisymmetric elements at the zenith of the dynamo region through electromagnetic skin effects [9, 13, 47, 48].

Stevenson's analysis, employing a Cartesian thin-layer approach, determined the extent of axisymmetrization within such a stratum. He deduced that axisymmetrization is expected to occur under conditions of substantial magnetic Reynolds numbers, thereby circumventing conflicts with Cowling's theorems, as non-axisymmetry remains finite, albeit potentially minuscule [33, 9, 8].

Moreover, Stevenson's distinctive model agree with the inferred depth of the dynamo generation region, which lies deeper than conventional Saturn models' estimations. This disparity arises because the inhomogeneous and stable metallic zone does not actively partake in the dynamo process. The thickness of this zone is approximated to be around 5000 km [1, 9, 36].

V. MERITS OF STEVENSON’S MODEL

Stevenson's model presents a compelling framework that effectively elucidates a multitude of phenomena observed within Saturn, shedding light on its enigmatic features. The model's main merits include:

1. **High Axisymmetry of Saturn's Magnetic Field:** Stevenson's model successfully accounts for the significant level of axisymmetry observed in Saturn's magnetic field. The presence of a stably stratified electrically conducting layer in the planet’s interior acts as a filter, suppressing the non-axisymmetric components of the magnetic field[1, 7,9-11,15].

2. **Depletion of Atmospheric Helium:** Stevenson's model could account for the intriguing depletion of atmospheric helium within Saturn. The model predicts that helium will tend to separate from hydrogen at high pressures and temperatures. This process, known as helium rain, leads to the sinking of helium droplets, which depletes the upper atmosphere of helium [31].

3. **Excess Luminosity:** Stevenson's model also accounts for the excess luminosity observed in Saturn. The mechanism elucidates that the process of helium precipitation not only expels latent energy but also facilitates consequential viscous dissipation. The cumulative effect of these energy transfers serves as a substantial contributor to Saturn's overall luminosity [31, 34, 49,51].

4. **Distinction from Jupiter's Dynamo:** Stevenson's model offers a natural explanation for the differences between the dynamos of Saturn and Jupiter. The demixing of hydrogen and helium, as proposed in his model, provides a basis for understanding the lower helium content and higher luminosity observed in Saturn compared to Jupiter [31,34,50,51**].**

VI. SUPPORT OF STEVENSON’S MODEL

Support for Stevenson's model has been obtained from various studies and numerical simulations:

1. **Kinematic and Dynamically Self-Consistent Dynamo Models:** Kinematic models [52,53] and dynamically self-consistent dynamo models [33,54] have provided support for Stevenson's model. These models have demonstrated that stably stratified layers surrounding dynamo regions can affect the symmetry of the generated magnetic field. The presence of thick and thin stably stratified layers has been shown to suppress rapidly varying, higher-order magnetic field components through a skin effect mechanism [40,11].

2. **The Transition from Molecular to Metallic Hydrogen:** The shift to metallic hydrogenfrom molecular, which occurs at intense pressures at approximately 140-200 GPa, corresponding to a depth of about 0.5 Saturn radii has been supported by theoretical studies and shock pressure measurements [37, 55 -57]. Additionally, calculations and experiments have indicated that helium and hydrogen don't mix well under extreme pressures at about 1 Mbar, which aligns with Stevenson's model [35].

3. **Kinematic Dynamo Studies:** Simulations by *Love (2000)*have revealed that the types of flows within electrically conductive fluids can impact the symmetry of the dynamo magnetic field[53]. *Schubert et. al. (2004)* showed that the way thermal winds move in the stable layer above the dynamo can also affect the magnetic field's shape [52].

4. **Numerical Dynamo Models:** *Christensen and Wicht (2008)* through their numerical dynamo models found that the differential rotation within the stable layer does indeed play a role in reducing non-symmetrical parts of the magnetic field, which lines up with Stevenson's proposed process **[54]**. Similarly, Stanley (2010) 3D dynamic dynamo models demonstrated that variations in temperature at the top of the stable layer can significantly affect the magnetic field's appearance **[33, 11].**

5. **Observational and Computational Investigations:** *Stanley and Bloxham (2016)* illustrated that Saturn's magnetic field components should experience an exceptionally slow change over time due to the theoretical outcome of Stevenson's axisymmetrization process [11]. *Cao and Stevenson (2017)* unveiled that a patterned differential rotation and

twisting motion within the semi-conducting layer could result in a magnetic spectrum that's symmetric around an axis **[58].** Building on this, *Cao et al. (2020)* scrutinized data from the Cassini Grand Finale mission and introduced the idea of a stable, electrically conductive layer situated above Saturn's deeper dynamo, which brings about magnetic axisymmetry [3]. Furthermore, *Yan and Stanley (2021)* numerical simulations reaffirmed the pivotal role played by a stable layer where helium "rains out," characterized by fluctuations in heat transfer, in explaining Saturn's magnetic field behaviour [35]. In another study, *Moore et al. (2021)* reported an absence of temporal variation in Saturn's internal magnetic field, which lends support to the notion of a stable layer positioned above the dynamo area [20, 11].

The above investigations bolster Stevenson's model by illustrating how stable layers can shape the magnetic field and demonstrating its alignment with real-world observations

VII. LIMITATIONS STEVENSON’S MODEL

Studies that present contrasting findings to Stevenson's proposed mechanism have emerged, shedding light on alternative factors that could impact the axisymmetry of Saturn's magnetic field:

1. **Complex Interactions in Stratified Layers:***Stanley and Mohammadi (2008)* demonstrated that having a thin stably stratified layer on its own doesn't necessarily result in the expected axisymmetrization of the magnetic field. Instead, they observed that interactions between stable and unstable layers generate thermal winds that can disrupt the dynamo process. This disruption leads to magnetic fields that aren't axisymmetric or dipolar, contradicting Stevenson's predictions. It's important to note that their model isn't a complete disproof of Stevenson's concept since they didn't account for the temperature variations from pole to equator, which Stevenson envisioned as a driving force for thermal winds within the layer [11,33,54, 59].

2. **Numerical Dynamo Simulations and Complex:** *Yadav et al. (2022*), in their numerical dynamo simulations, found that without introducing additional elements like varying heat flux patterns or stable stratified layers it quite tough to achieve the small tilt angles of the magnetic dipole – a crucial aspect for axisymmetry. They also demonstrated that some dynamo models could indeed produce nearly negligible dipole tilt angles (averaging about ≈ 0.0008°) without involving stably stratified layers or imposed heat flux variations. The twist here is that even though small dipole tilt angles are necessary, they alone aren't sufficient to fully describe the highly symmetrical magnetic field seen on Saturn. A dynamo could exhibit significant magnetic field fluctuations around the planet's equator while still having minimal dipole tilt angles, provided these field fluctuations mirror each other across the equator [4].

In essence, these studies provide counterarguments to Stevenson's mechanism by presenting alternative elements that might influence the symmetry of Saturn's magnetic field. While they emphasize the intricate nature of explaining the observed magnetic field, they don't completely invalidate Stevenson's proposed theory. Rather, they underscore the need for further research, encompassing additional factors and accounting for the envisioned temperature variations, to attain a comprehensive grasp of the forces shaping Saturn's magnetic behaviour.

VIII. CHALLENGES OF THE ACCURATE MODELLING

1. **Uncertainty in Rotational Rate:** The different conceptual frameworks for Saturn's inner magnetic field shared a common characteristic: they displayed inherent symmetry around its rotational axis. This symmetry arose because of the lack of precise information regarding Saturn's rotational speed. Without a reliable understanding of this rotational rate, it was unfeasible to create an internal magnetic field model that integrated elements deviating from the axial orientation. In these proposed models, any magnetic field components not aligned with the axis would have been distributed across a broad span of longitudes, leading to a diluted and uncertain impact [26].

2. **Uncertainty in Atmospheric Helium Mass Fraction:** Accurate knowledge of the atmospheric helium mass fraction is essential for constraining models of Saturn's magnetic field and gaining a better understanding of Saturn's internal structure and composition [60]. The presence of helium in the atmosphere affects the density structure and flow field, which in turn affects the planet's gravity harmonics [61]. The gravity harmonics measured by the Cassini mission provide valuable information about the depth to which Saturn's zonal winds penetrate below the cloud level [62].

3. **Uncertainty in Atmospheric Helium Mass Fraction**: Flow-induced gravity signals can be used to study the large-scale evolution of the viscous overstability in Saturn's rings [63]. By studying the interaction of atmospheric gravity waves with the ionosphere, the complex vertical structure of Saturn's lower ionosphere can be explained [64]. Therefore, accurate knowledge of the atmospheric helium mass fraction and flow-induced gravity signals is crucial for understanding the dynamics, interior density structure, composition, magnetic field, and core mass of Saturn **[26].**

IX. DISCUSSIONS

The precise process by which the asymmetrical magnetic field generated within Saturn's dynamo region is converted into a symmetrical field outside the planet remains incompletely comprehended. Cowling's Theorem pertains to the magnetic field originating within a planet's dynamo region, rather than the symmetrical magnetic field observed beyond the planet. Should there exist a mechanism capable of transforming the internal non-axisymmetric field into an external axisymmetric one, it would not contradict Cowling's Theorem. One conceivable means of effecting this transformation is through shear instability, which arises when fluid motion varies in speed across different latitudes, resulting in a magnetic field aligned with the planet's rotational axis. Another potential mechanism is meridional circulation, where fluid moves from the equator toward the poles, thereby generating a magnetic field that aligns with the rotational axis [65,66].

An alternative explanation for this transformation is related to the Ekman layer, a thin fluid layer found at the boundary between a rotating and stationary fluid. The Ekman layer can induce a shearing flow, potentially leading to the creation of an axisymmetric magnetic field [53,67]. Another plausible mechanism is the magnetic buoyancy instability, in which a magnetic field becomes buoyant within a fluid and rises to the planet's surface, eventually becoming axisymmetric [68]. These mechanisms offer potential insights into the magnetic field transformation, although more research is necessary to fully grasp this process.

Furthermore, various physical processes and components, such as a shallower dynamo above the stable layer [45,3], radially varying electrical conductivity [69], and double-diffusive convection in the helium rain-out layer [35], necessitate further investigation [70]. Fluid movements triggered by the Coriolis force can naturally occur in convecting fluids, even in slowly rotating planets like Venus [71,72,76]. Additionally, it's conceivable that a secondary dynamo action takes place in Saturn due to deep zonal flows and small-scale convective motion in the semiconducting region [6,10,41,73]. These phenomena have not been exhaustively explored and demand additional research to comprehend their implications and impact on the generation of magnetic fields in celestial bodies [74]

X. CONCLUSION

Saturn's internal magnetic field, distinguished by its near-perfect axisymmetry, has remained a scientific puzzle. There are several mechanisms that can provide potential explanations for the axisymmetrization of Saturn’s internal magnetic field, but further research is needed to fully understand this process. Various models and theories have been proposed to explain this unique characteristic, with Stevenson's theory gaining prominence. While Stevenson's mechanism offers a compelling framework, challenges arise from the complex interactions within stratified layers and the influence of non-axisymmetric elements. The alignment of Saturn's magnetic field with its rotational axis contradicts Cowling's Theorem, requiring exploration of potential mechanisms such as shear instability and magnetic buoyancy instability. In addition, the roles of fluid motions driven by the Coriolis force and potential secondary dynamo actions are avenues for further investigation. Since accurate rotational data, atmospheric helium mass fraction, and flow-induced gravity signals are imperative for accurate modeling future missions to Saturn should focus on the measurement or collection of data from various angles and locations near Saturn.Also, synthesizing improved numerical modeling methods and computational power will contribute to a better understanding of its internal magnetic field.

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