A New Physical Model of Lightning Initiation and Propagation

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Abstract

Lightning remains one of the most complex and incompletely understood phenomena in atmospheric physics. While the existence of ionized plasma channels, large electric currents, strong magnetic fields, and intense electromagnetic radiation is well established experimentally, the physical mechanism responsible for the initiation and sustained propagation of lightning leaders is still the subject of active investigation.

This paper proposes a new working hypothesis in which lightning propagation is interpreted as the evolution of a ***Self-Organizing Electromagnetic Tube (SOET)****. According to the proposed model, localized impulsive electric fields inside thunderstorms generate numerous short-lived current pulses. Most of these pulses decay rapidly, producing the continuous electrical crackling commonly observed in thunderstorms. When an impulsive current exceeds a critical threshold, however, the surrounding magnetic field is hypothesized to undergo a transition into a self-organizing electromagnetic structure capable of continuously interacting with the surrounding partially ionized plasma.*

Within the proposed mechanism, SOET organizes the motion of electrons and positive ions into counter-propagating charge streams. Because electrons respond much more rapidly than ions, a temporary difference between their average velocities generates the strong electric current required to sustain the magnetic field. The electromagnetic structure is therefore maintained by a positive feedback process linking organized plasma motion, electric current, and magnetic-field amplification.

The model further proposes that the exceptionally high temperatures of lightning arise naturally from energetic collisions between the counter-propagating electron and ion streams. The finite lifetime of lightning is interpreted as a consequence of the gradual relaxation of the plasma: as collisions progressively equalize the average velocities of electrons and ions, the current decreases, the magnetic field weakens, and the self-organizing electromagnetic structure disappears.

The proposed hypothesis provides a unified qualitative interpretation of several characteristic features of lightning, including atmospheric crackling, critical lightning initiation, stepped leader propagation, plasma heating, branching, and lightning termination. It also produces experimentally testable predictions, including the existence of a localized propagating electromagnetic structure at the leader head, a characteristic SOET length, a critical current for self-organization, and specific correlations between crackling activity and lightning initiation.

Although qualitative in its present form, the proposed model establishes a physical framework for a future quantitative theory based on coupled electromagnetic and plasma dynamics. If confirmed experimentally, the concept of a Self-Organizing Electromagnetic Tube may represent a general mechanism of electromagnetic self-organization in partially ionized plasmas, extending beyond terrestrial lightning to other natural plasma environments.

1. Introduction

Lightning is one of the most energetic and visually impressive natural phenomena occurring in the Earth's atmosphere. Despite more than a century of intensive research, several fundamental aspects of lightning initiation and propagation remain incompletely understood. Modern lightning theory successfully explains many observed characteristics, including the existence of ionized plasma channels, large electric currents, electromagnetic radiation over a broad frequency range, and the generation of high temperatures. However, the physical mechanism that enables a lightning leader to propagate over long distances through a highly dynamic atmosphere is still the subject of active research.

The conventional description assumes that charge separation inside thunderclouds creates strong electric fields, which eventually exceed the local breakdown threshold of air. Ionization then produces conductive channels that allow large electric currents to flow. While this framework explains many features of lightning, it also encounters several well-known difficulties. Balloon and aircraft measurements frequently report electric fields considerably lower than the classical breakdown field of dry air, suggesting that additional physical mechanisms may contribute to the initiation and sustained propagation of lightning channels.

Thunderstorms also exhibit numerous transient electrical events before the appearance of a fully developed lightning discharge. Continuous crackling, short luminous discharges, impulsive electric-field variations, and bursts of radio-frequency emission indicate that the atmosphere is populated by numerous short-lived electromagnetic events. Most of these events disappear within microseconds or milliseconds, while only a very small fraction develops into a large lightning discharge. The physical criterion that distinguishes decaying disturbances from those that evolve into self-sustaining lightning remains insufficiently understood.

In this work we explore the possibility that these transient events represent the initial stage of a self-organizing electromagnetic process. We propose the working hypothesis that a sufficiently strong impulsive current can generate a localized electromagnetic structure which subsequently interacts with the surrounding plasma in a positive feedback process. Once a critical condition is exceeded, the structure becomes capable of organizing the motion of electrons and ions, thereby maintaining the electric current that simultaneously sustains the magnetic field responsible for its own stability. We refer to this hypothetical structure as a **Self-Organizing Electromagnetic Tube (SOET)**.

Within this hypothesis, the lightning channel is not viewed merely as a passive conductive path created by an external electric field. Instead, the propagating head of the discharge is considered an active electromagnetic structure that continuously exchanges energy and momentum with the surrounding ionized medium. The difference in the dynamical response of electrons and positive ions, arising primarily from their large mass difference, naturally leads to the formation of strong electric currents, intense magnetic fields, plasma heating, and the gradual evolution of the lightning channel.

The proposed model aims to provide a unified qualitative explanation for several characteristic features of lightning, including impulsive initiation, crackling preceding major discharges, stepped leader propagation, high plasma temperatures, strong electromagnetic radiation, and the finite lifetime of lightning channels. Rather than replacing the established principles of classical electromagnetism, the model investigates whether self-organization within a conducting plasma may play a more significant role in lightning dynamics than is usually assumed.

The objective of this paper is therefore not to challenge Maxwell's electromagnetic theory, but to examine whether the observed properties of lightning can be consistently interpreted by introducing a self-organizing electromagnetic structure as the principal propagating entity. The following sections develop the physical motivation for this hypothesis, formulate its underlying mechanism, and derive its principal consequences together with experimentally testable predictions.

2. Experimental Characteristics of Lightning

Lightning is among the most extensively observed atmospheric electrical phenomena. Modern optical, electrical, radio-frequency, and satellite measurements have revealed numerous characteristics that are well established experimentally. While existing models successfully explain many individual observations, no single physical description has yet achieved universal acceptance for the complete sequence from lightning initiation to channel propagation and decay. Any new model should therefore be consistent with the following experimentally established properties.

The development of a lightning discharge is commonly preceded by numerous short-lived electrical events within the thundercloud. These events are observed as continuous crackling, small luminous discharges, impulsive electric-field variations, and bursts of radio-frequency emission. Most of these transient events disappear within microseconds or milliseconds without developing into a full lightning discharge. Only a very small fraction evolves into a propagating lightning leader.

High-speed optical observations show that lightning leaders do not usually propagate continuously. Instead, negative leaders typically advance in discrete steps separated by short pauses. Individual steps are commonly several metres to several tens of metres long, indicating that the propagation process itself is intermittent rather than continuous.

Measurements performed using balloon probes, aircraft, and ground-based instruments show that thunderclouds contain highly non-uniform electric fields. Local electric-field pulses of short duration are frequently observed before and during lightning development. Although large electric fields undoubtedly exist within thunderstorms, the measured values are often lower than the classical breakdown field of dry air, suggesting that local transient processes play an important role in discharge initiation.

Once a conductive channel is established, extremely large electric currents are generated. Peak currents commonly reach several tens of kiloamperes, while exceptionally strong discharges may exceed one hundred kiloamperes. According to classical electromagnetism, such currents inevitably produce intense magnetic fields surrounding the lightning channel.

Lightning channels rapidly heat the surrounding air to temperatures approaching approximately 30,000 K. At these temperatures the channel becomes a highly ionized plasma emitting intense visible and infrared radiation. The rapid thermal expansion of the plasma produces the acoustic shock wave perceived as thunder.

Lightning is also an exceptionally strong source of electromagnetic radiation. Emissions have been detected over nearly the entire electromagnetic spectrum, ranging from extremely low frequency (ELF) radio waves through VHF radio emission, infrared and visible light, ultraviolet radiation, X-rays, and, in some cases, terrestrial gamma-ray flashes. This broad spectrum indicates that multiple physical processes occur simultaneously within the discharge.

Despite the large currents and high temperatures, lightning channels remain transient structures. The luminous plasma channel exists only for a limited time before cooling, recombining, and disappearing. Even within a single flash, the electrical current often consists of multiple successive return strokes separated by relatively short intervals, demonstrating that the conductive channel itself is not permanently self-sustaining.

An additional characteristic of thunderstorms is the statistical relationship between numerous small electrical events and the relatively rare occurrence of a major lightning discharge. The atmosphere continuously produces a large number of short-lived electrical disturbances, whereas only a very small number reach the scale of a fully developed lightning channel. This observation suggests the existence of a critical physical condition separating decaying transient events from self-sustaining propagating structures.

The present work adopts these experimentally observed properties as the primary constraints for the proposed physical model. Rather than introducing new electromagnetic laws, the objective is to investigate whether all of these observed characteristics can be interpreted as different manifestations of a single self-organizing electromagnetic process.

3. The Initial Impulsive Current

The observations summarized in the previous section indicate that thunderstorms continuously produce numerous localized electric-field impulses. Most of these transient events disappear within a very short time, while only a small fraction develops into a propagating lightning discharge. The present model assumes that the decisive event is the formation of a sufficiently strong initial current pulse.

A localized impulsive electric field accelerates both electrons and positive ions present within the partially ionized atmospheric plasma. Because the electron mass is several thousand times smaller than the ion mass,

$$m_e \ll m_i,$$

electrons respond almost immediately to the electric field, whereas the much heavier positive ions accelerate considerably more slowly. Consequently, the initial current is dominated by the electron component.

The resulting current pulse generates a toroidal magnetic field surrounding the current channel according to Ampère's law. This process is entirely consistent with classical electromagnetism and requires no additional assumptions. Every sufficiently strong current necessarily produces a surrounding magnetic field.

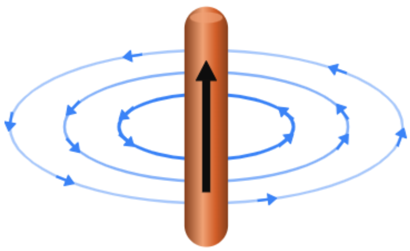

Figure 1. *A localized impulsive current naturally generates a toroidal magnetic field according to Ampère's law. Within the proposed model, most such current pulses remain too weak to organize the surrounding plasma and therefore decay rapidly. Only sufficiently strong impulsive currents may evolve into a self-organizing electromagnetic structure.*

The present hypothesis proposes that most current pulses remain too weak or too short-lived to influence the surrounding plasma significantly. These pulses rapidly decay and correspond to the numerous transient electrical events observed as crackling inside thunderstorms.

A fundamentally different evolution becomes possible when the initial current exceeds a critical intensity. In this case, the magnetic field surrounding the current is assumed to become sufficiently strong to organize the motion of charged particles within its vicinity. Instead of representing only a passive consequence of the current, the electromagnetic field becomes an active participant in the subsequent plasma dynamics.

The transition is therefore described as a threshold phenomenon. Below a critical current,

$$I < I_c,$$

the current pulse decays rapidly because collisions, recombination, and momentum exchange with the surrounding air dissipate the initial disturbance. Above the critical value,

$$I > I_c,$$

the electromagnetic field becomes capable of maintaining an organized interaction with the surrounding plasma. This marks the formation of the proposed **Self-Organizing Electromagnetic Tube (SOET)**.

Within this working hypothesis, SOET is not assumed to originate spontaneously. Instead, it emerges naturally from an ordinary impulsive current whenever the electromagnetic interaction becomes sufficiently strong to overcome local dissipative processes. In this sense, SOET represents a new dynamical state of the plasma rather than an independent physical entity.

The formation of SOET provides a possible explanation for the observed statistical behaviour of thunderstorms. Numerous impulsive electric-field events continuously generate short-lived current pulses, but only the rare pulses exceeding the critical condition evolve into stable propagating electromagnetic structures. This naturally explains why continuous crackling is commonly observed inside thunderstorms, whereas fully developed lightning discharges occur comparatively infrequently.

The following section investigates how the newly formed SOET interacts with the surrounding plasma and how this interaction may lead to the self-amplifying propagation of the lightning channel.

4. Critical Transition to a Self-Organizing Electromagnetic Tube (SOET)

The impulsive current described in the previous section is assumed to represent the initial state from which two fundamentally different evolutionary paths are possible. Most current pulses dissipate rapidly and disappear within a very short time. Only a small fraction develops into a stable propagating structure. The present hypothesis proposes that this transition is governed by a critical condition separating ordinary transient current pulses from self-organizing electromagnetic structures.

Immediately after its formation, the impulsive current produces a toroidal magnetic field surrounding the current channel. At low current intensities, this magnetic field remains too weak to significantly influence the surrounding plasma. The current therefore decays through ordinary dissipative processes, including collisions, recombination, and momentum exchange with the neutral atmosphere.

A qualitatively different regime becomes possible when the current exceeds a critical intensity. The magnetic field is then assumed to become sufficiently strong to organize the motion of nearby charged particles. Instead of remaining merely a passive consequence of the electric current, the electromagnetic field begins to participate actively in the plasma dynamics.

The proposed transition is illustrated schematically by

$$\begin{aligned} I < I_c \quad &\Longrightarrow \quad \text{ordinary current pulse,} \\ I > I_c \quad &\Longrightarrow \quad \text{formation of SOET.} \end{aligned}$$

The critical current I_c should not be regarded as a universal constant. It is expected to depend on local plasma density, ionization level, humidity, pressure, temperature, and the concentration of charged particles present within the thundercloud. The present work therefore introduces I_c only as a phenomenological threshold separating two different dynamical regimes.

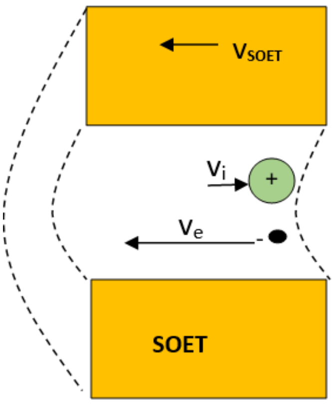

Figure 2. *Schematic illustration of the proposed interaction between the propagating Self-Organizing Electromagnetic Tube (SOET) and the surrounding partially ionized plasma. As SOET advances, electrons rapidly respond to the electromagnetic field, whereas the heavier positive ions accelerate more slowly. The resulting temporary difference between the average electron and ion velocities generates the electric current sustaining the magnetic field of SOET. This establishes the positive feedback responsible for the self-organization of the propagating electromagnetic structure.*

Once the transition occurs, the electromagnetic structure is assumed to acquire its own dynamical stability. Charged particles continuously enter the moving structure from the surrounding plasma. Because electrons respond much more rapidly than positive ions, the two particle populations acquire different average velocities while interacting with the electromagnetic field. This difference generates a large electric current, which in turn strengthens the magnetic field responsible for maintaining the structure itself.

The proposed mechanism therefore establishes a positive feedback process:

impulsive current → magnetic field → organized plasma motion → stronger current → stronger magnetic field.

The transition from an ordinary current pulse to SOET is thus interpreted as a self-organization process. The electromagnetic field does not create charged particles, nor does it generate electric current independently. Instead, it progressively organizes the motion of the electrons and ions already present within the partially ionized atmosphere. The organized motion of these charged particles maintains the current, while the current simultaneously maintains the electromagnetic structure.

Within this model, the continuous crackling observed inside thunderstorms corresponds to numerous impulsive current pulses that remain below the critical condition and therefore decay rapidly. A fully developed lightning discharge represents the comparatively rare situation in which one of these impulsive currents successfully undergoes the transition into a stable Self-Organizing Electromagnetic Tube. Once established, the SOET propagates through the surrounding plasma while continuously exchanging energy and momentum with charged particles encountered along its path.

This interpretation naturally explains why thunderstorms produce an enormous number of short-lived electrical events, whereas only a very small number develop into large lightning discharges. The decisive factor is not the existence of impulsive currents themselves, but whether one of them reaches the conditions necessary for electromagnetic self-organization.

The central hypothesis of the present work is that, above a critical current, the magnetic field surrounding the impulsive discharge becomes sufficiently strong to organize the motion of charged particles within the surrounding plasma. The resulting increase in organized current further strengthens the magnetic field, establishing a self-sustaining electromagnetic structure.

5. Interaction Between SOET and Plasma

The formation of a Self-Organizing Electromagnetic Tube (SOET) marks the transition from a short-lived impulsive current into a dynamically evolving electromagnetic structure. Unlike an ordinary current pulse, SOET continuously interacts with the surrounding plasma while propagating through the thundercloud. The plasma is therefore not merely the medium in which the structure exists, but an essential component of its dynamics.

The atmosphere surrounding the propagating SOET contains a partially ionized mixture of free electrons, positive ions, neutral molecules, and small charged particles. These charged particles possess random thermal velocities and continuously collide with one another. Before interacting with SOET, no preferred direction of motion exists on the macroscopic scale.

As the electromagnetic structure propagates through the plasma, charged particles continuously enter its region of influence. The interaction is not limited to individual particle collisions. Instead, SOET acts collectively on a large population of charged particles occupying its entire volume. The electromagnetic field progressively organizes their otherwise random motion into partially ordered charge streams.

The interaction involves a continuous exchange of both energy and momentum between the electromagnetic structure and the surrounding plasma. Because every localized electromagnetic field possesses energy and therefore effective inertia, SOET participates dynamically in this exchange rather than acting as a passive magnetic field. The plasma modifies the electromagnetic structure, while the electromagnetic structure simultaneously modifies the plasma.

A fundamental property of the interaction arises from the large difference between the masses of electrons and positive ions,

$$m_e \ll m_i.$$

Consequently, electrons respond much more rapidly to the electromagnetic forces than the considerably heavier ions. During the initial stage of the interaction, the average electron velocity increases much faster than the average ion velocity. The plasma therefore develops a temporary difference between the average velocities of the two charge populations.

Within the proposed model, this velocity difference constitutes the primary source of the electric current sustaining SOET. The current is therefore not imposed externally but develops naturally through the different dynamical response of electrons and ions interacting with the moving electromagnetic structure.

The interaction is not stationary. As charged particles continue exchanging momentum through collisions, the average ion velocity gradually approaches the average electron velocity. Simultaneously, collisions and recombination reduce the number of freely moving charge carriers. Both processes progressively decrease the current that sustains the electromagnetic structure.

An important consequence of this mechanism is that SOET possesses a finite lifetime without requiring any additional decay process. The same plasma interaction that initially strengthens the organized current eventually destroys it by reducing the velocity difference between electrons and ions. The electromagnetic structure therefore continuously evolves through growth, saturation, and decay while propagating through the atmosphere.

The proposed interaction mechanism may be summarized schematically as

$$\text{SOET} \Longleftrightarrow \text{Plasma}$$

where the double arrow represents a continuous exchange of

- electromagnetic energy,
- momentum,
- organization of charged-particle motion.

Within this framework, SOET should not be regarded as an isolated electromagnetic object. It exists only through its continuous interaction with the surrounding plasma. The propagating structure and the plasma therefore form a single coupled dynamical system whose evolution determines the initiation, propagation, and eventual disappearance of the lightning channel.

6. Formation of Opposite Charge Streams

The interaction between SOET and the surrounding plasma leads to the gradual formation of two oppositely directed charge streams. This process represents the fundamental mechanism by which the electromagnetic structure maintains the electric current required for its own existence.

Initially, electrons and positive ions are distributed throughout the partially ionized atmosphere with no preferred direction of motion. Their velocities are dominated by random thermal motion and frequent collisions with neutral molecules. The impulsive electric field responsible for initiating SOET provides the first ordered motion, after which the electromagnetic structure itself governs the subsequent plasma dynamics.

Because electrons possess a much smaller mass than positive ions,

$$m_e \ll m_i,$$

their response to the moving electromagnetic structure is considerably faster. Electrons rapidly acquire an organized drift motion, whereas the heavier ions respond more slowly. As a consequence, the plasma develops two distinct charge streams with different average velocities.

Within the proposed model, the electron and ion streams propagate in opposite directions along the axis of the electromagnetic tube. The electric current therefore results from the combined motion of both charge populations rather than from the motion of electrons alone.

The corresponding current density may be written as

$$\mathbf{J} = en_i\mathbf{v}_i - en_e\mathbf{v}_e,$$

where

- $\mathbf{n_e}$ and $\mathbf{n_i}$ are the number densities of electrons and positive ions,
- $\mathbf{v_e}$ and $\mathbf{v_i}$ denote their average drift velocities.

Because the electron and ion velocities are directed oppositely, their contributions to the electric current reinforce one another. The resulting current may therefore become considerably larger than would be expected from the electron motion alone.

An important consequence of the counter-propagating charge streams is the large relative velocity between electrons and ions. Although both populations remain confined within the same plasma volume, their mutual collisions become increasingly energetic. These collisions continuously convert part of the organized kinetic energy into thermal energy, naturally producing the extremely high plasma temperatures observed in lightning channels.

The organized charge streams do not remain constant indefinitely. As momentum is continuously exchanged through collisions, the average ion velocity gradually approaches the electron velocity. At the same time, recombination and scattering progressively reduce the number of free charge carriers. Consequently, the current sustaining SOET slowly decreases.

The present model therefore attributes the existence of the electric current primarily to the temporary dynamical asymmetry between electron and ion motion. The current is not maintained by a permanent external driving field but by the transient difference in the average velocities of the two charge populations while they interact with the moving electromagnetic structure.

This interpretation differs from the conventional picture of a plasma channel carrying a single conduction current. Instead, the lightning channel is regarded as a coupled system of counter-propagating electron and ion streams whose temporary imbalance generates the intense current required to sustain the electromagnetic structure.

The evolution of the process may be summarized schematically as

$$v_e \gg v_i \implies J_{\max} \implies B_{\max},$$

followed by

$$v_i \to v_e \implies J \to 0 \implies B \to 0.$$

Thus, the formation and subsequent equalization of the opposite charge streams naturally explain both the growth and the eventual decay of the Self-Organizing Electromagnetic Tube.

7. Magnetic Amplification

The persistence of SOET depends on its ability to maintain the electric current responsible for the surrounding magnetic field. Since the magnetic field itself influences the organization of charged-particle motion, the electromagnetic structure forms a self-consistent feedback system. The stability of SOET therefore depends on the balance between magnetic amplification and dissipative losses.

Within the proposed model, the moving electromagnetic structure continuously interacts with the surrounding plasma. Electrons respond rapidly to this interaction, whereas the considerably heavier positive ions respond more slowly. As discussed in the previous section, this difference produces a temporary velocity difference

$$\Delta v = v_e - v_i,$$

which generates the electric current sustaining the structure.

The corresponding current density is

$$J = en\,\Delta v,$$

where n denotes the effective density of free charge carriers.

According to Ampère's law, the current immediately produces a magnetic field surrounding the current channel,

$$B \propto J.$$

The magnetic field therefore increases automatically whenever the difference between the average electron and ion velocities increases.

The proposed hypothesis assumes that the strengthened magnetic field improves the organization of charged-particle motion inside SOET. The improved organization increases the velocity difference between electrons and ions, thereby increasing the current. A positive feedback loop is therefore established,

$$\mathrm{SOET} \to \Delta v \to J \to B \to \mathrm{SOET}.$$

The amplification process cannot continue indefinitely. Several dissipative mechanisms act simultaneously:

- collisions between charged particles and neutral molecules,
- electron-ion collisions,
- recombination,
- gradual equalization of electron and ion velocities,
- radiation losses.

These processes continuously reduce both the number of free charge carriers and the velocity difference responsible for the current.

The evolution of SOET is therefore determined by the competition between magnetic amplification and dissipation. Instead of introducing separate amplification and loss mechanisms, the present model characterizes the overall evolution by a dimensionless amplification factor

$$R = \frac{P_{\mathrm{amp}}}{P_{\mathrm{loss}}},$$

where P_{amp} denotes the power transferred from the organized plasma motion into the electromagnetic structure, while P_{loss} represents the total dissipative power.

Three dynamical regimes are then possible.

For

$$R < 1,$$

dissipation dominates. The current decreases continuously, the magnetic field weakens, and SOET disappears after a short lifetime.

For

$$R = 1,$$

magnetic amplification exactly balances dissipation. The electromagnetic structure propagates with approximately constant properties.

For

$$R > 1,$$

magnetic amplification exceeds the losses. The current increases, the magnetic field becomes stronger, and the electromagnetic structure grows until limited by nonlinear plasma processes.

This critical balance naturally explains the observed behaviour of thunderstorms. The vast majority of impulsive current pulses correspond to

$$R < 1,$$

and therefore decay rapidly, producing only short-lived crackling events. Only the comparatively rare fluctuations reaching

$$R \geq 1$$

develop into stable propagating SOET structures capable of evolving into complete lightning channels.

The present hypothesis therefore attributes lightning propagation to a dynamic equilibrium rather than to a continuously increasing current. During propagation, SOET continuously exchanges energy and momentum with the surrounding plasma while simultaneously losing energy through collisions and radiation. Stable propagation becomes possible only when these competing processes remain in approximate balance over an extended period.

8. Plasma Heating

The exceptionally high temperatures observed in lightning channels represent one of the most characteristic features of atmospheric electrical discharges. Spectroscopic measurements indicate plasma temperatures approaching 30,000 K, implying that enormous amounts of kinetic energy are continuously converted into thermal energy during the discharge.

Within the conventional description, plasma heating is generally attributed to Joule dissipation produced by large electrical currents flowing through the conductive channel. While this mechanism undoubtedly contributes to the overall energy balance, the present model proposes that an additional heating mechanism naturally follows from the interaction between SOET and the surrounding plasma.

As described in the previous section, the propagating electromagnetic structure organizes the plasma into two counter-propagating charge streams composed primarily of electrons and positive ions. The electron stream responds rapidly to the moving electromagnetic structure, whereas the heavier ions accelerate more slowly. During the active stage of SOET, both charge populations coexist within the same plasma volume while moving with substantially different average velocities.

Since the electron and ion streams propagate in opposite directions along the SOET axis, the relative collision velocity is equal to the sum of their average velocities,

$$v_{\text{rel}} = v_e + v_i.$$

Consequently, the kinetic energy available in electron-ion collisions is proportional to

$$E_{\text{coll}} \propto (v_e + v_i)^2.$$

Even moderate drift velocities of the two counter-propagating charge streams therefore produce highly energetic collisions. These collisions continuously transform organized kinetic energy into thermal energy, naturally explaining the extremely high temperatures observed within lightning channels.

Because electrons and ions continuously collide while possessing large relative velocities, each collision converts part of their organized kinetic energy into random thermal motion. Instead of representing an undesirable loss process, these collisions constitute the principal source of plasma heating within the proposed model.

The thermal energy generated by these collisions raises the plasma temperature sufficiently to maintain a highly ionized state. Frequent energetic collisions also contribute to repeated impact ionization, continuously producing new free charge carriers that support the electrical conductivity of the plasma. The high temperature is therefore not merely a consequence of the discharge but also contributes to maintaining the conductive environment required for SOET propagation.

The heating process may therefore be summarized as

SOET → organized counter-> streaming charges → energetic collisions → thermal energy → high plasma conductivity.

This sequence establishes an additional positive coupling within the lightning channel. Increased conductivity allows stronger organized currents to develop, while stronger currents sustain the magnetic field responsible for maintaining the electromagnetic structure.

The same collision processes that heat the plasma also represent an important source of energy dissipation. Every collision simultaneously performs two functions: it converts organized kinetic energy into thermal energy and gradually reduces the velocity difference between electrons and ions. Consequently, plasma heating contributes both to the stability of the conductive channel and to the eventual decay of the electromagnetic structure.

Within the proposed model, the high temperature of lightning is therefore interpreted as a natural consequence of the collective interaction between SOET and the surrounding plasma. No additional heating mechanism beyond the interaction of the organized electron and ion streams is required. The plasma temperature reflects the continuous conversion of ordered electromagnetic energy into random thermal motion throughout the lifetime of the propagating electromagnetic structure.

9. Decay of SOET

The same interaction between SOET and the surrounding plasma that enables the electromagnetic structure to grow also determines its eventual disappearance. Within the proposed model, no additional physical mechanism is required to terminate the lightning discharge. The decay of SOET follows naturally from the progressive evolution of the organized charge streams.

During the active stage of SOET, electrons and positive ions propagate through the electromagnetic structure with substantially different average velocities. Because the electron stream responds rapidly to the moving electromagnetic field while the ions accelerate more slowly, a large velocity difference is established,

$$\Delta v = v_e - v_i.$$

This velocity difference produces the strong electric current sustaining the magnetic field of SOET.

As the interaction continues, repeated collisions continuously exchange momentum between the two charge populations. The heavier ions gradually accelerate, while the electron motion becomes increasingly affected by collisions with ions and neutral molecules. Consequently, the average velocities of the two charge populations progressively approach one another,

$$v_i \to v_e.$$

Since the electric current depends directly on the difference between the average velocities,

$$J = en(v_e - v_i),$$

the current decreases continuously as the two populations approach dynamical equilibrium.

The reduction of the current immediately weakens the magnetic field surrounding the electromagnetic structure. Because the magnetic field is responsible for organizing the plasma motion, its weakening reduces the ability of SOET to maintain the organized charge streams. This establishes a negative feedback process,

$$v_i \to v_e \Longrightarrow J \downarrow \Longrightarrow B \downarrow \Longrightarrow \text{SOET weakens.}$$

At the same time, energetic collisions between electrons and ions convert an increasing fraction of the organized kinetic energy into random thermal motion. These collisions also promote recombination and gradually reduce the concentration of free charge carriers available for maintaining the current. Both processes further decrease the magnetic field supporting the electromagnetic structure.

Eventually, the magnetic field becomes too weak to preserve the organized motion of the plasma. The remaining charged particles return to predominantly random thermal motion, the organized current disappears, and the electromagnetic structure ceases to exist.

The complete decay sequence may therefore be summarized as

$$v_e - v_i \to 0$$

$$\Longrightarrow$$

$$J \to 0$$

$$\Longrightarrow$$

$$B \to 0$$

$$\Longrightarrow$$

$$\text{SOET disappears.}$$

An important consequence of this mechanism is that the lifetime of SOET is determined primarily by the rate at which the electron and ion velocities approach equilibrium. The duration of the electromagnetic structure is therefore expected to depend on plasma density, collision frequency, ionization level, and the local concentration of charged particles rather than on a predetermined geometrical length.

Within the proposed model, lightning termination is thus interpreted as the natural relaxation of a self-organizing plasma system toward dynamical equilibrium. The same physical processes that initially generate the organized current ultimately eliminate the velocity difference required to sustain it.

10. Propagation of Lightning

Within the proposed model, lightning propagation is interpreted as the continuous evolution of a Self-Organizing Electromagnetic Tube (SOET) moving through a partially ionized atmosphere. Rather than representing a passive conductive channel created by a pre-existing electric field, the lightning leader is regarded as an active electromagnetic structure that continuously exchanges energy and momentum with the surrounding plasma.

The propagation begins when an impulsive electric field generates a sufficiently strong initial current. If this current exceeds the critical threshold discussed in the previous sections, a SOET is formed. Once established, the electromagnetic structure propagates through the surrounding plasma while continuously capturing electrons and positive ions from the adjacent atmosphere.

As charged particles enter the moving SOET, their initially random motion becomes progressively organized. Because electrons respond much more rapidly than positive ions, two counter-propagating charge streams are established. The resulting electric current strengthens the magnetic field surrounding the structure, allowing SOET to maintain its own organization while advancing into previously undisturbed plasma.

Unlike a conventional conductive channel, the electromagnetic structure continuously renews itself. At the leading edge, new charged particles are incorporated into the organized motion. Simultaneously, particles located farther behind the leading edge gradually approach dynamical equilibrium through collisions and momentum exchange. Consequently, the organized current weakens in the rear part of the structure while a new organized region is continuously formed at the front.

The propagation may therefore be viewed as a travelling region of electromagnetic self-organization rather than as the motion of a fixed physical object. The plasma forming the organized current is continuously replaced as the structure advances through the atmosphere. Only the organized electromagnetic state propagates, while individual charged particles remain within the structure only temporarily.

This behaviour resembles many propagating nonlinear phenomena in physics, where the moving structure persists although the individual particles participating in it are continuously exchanged. The identity of SOET is therefore determined by the self-organized electromagnetic configuration rather than by a permanent set of charged particles.

The finite lifetime of the organized plasma behind the leading edge naturally explains why lightning channels eventually decay. As electron and ion velocities gradually approach equilibrium, the organized current decreases and the magnetic field weakens. Meanwhile, the leading edge continuously encounters fresh plasma capable of sustaining the next stage of propagation. Lightning therefore advances through a continuous sequence of plasma organization at the front and plasma relaxation behind it.

The proposed mechanism also provides a natural interpretation of the stepped propagation observed in negative lightning leaders. Numerous impulsive electric-field events occur continuously within thunderstorms, but only some satisfy the conditions required for the formation of a stable SOET. Each successful formation event extends the lightning channel by creating a new region of organized plasma. The observed stepping behaviour is therefore interpreted as a succession of discrete self-organization events rather than as repeated dielectric breakdown of previously undisturbed air.

Branching may also arise naturally within this framework. If several neighbouring impulsive current pulses simultaneously satisfy the critical conditions for SOET formation, multiple electromagnetic structures may begin to develop. Competition for available charged particles and electromagnetic energy then determines which branches continue propagating and which disappear. The frequently observed irregular branching of lightning channels may therefore reflect the nonlinear competition between simultaneously evolving SOET structures.

Within the present hypothesis, the complete evolution of a lightning discharge may be summarized by the following sequence:

Impulsive electric field

$\Downarrow$

Initial current pulse

$\Downarrow$

Formation of SOET

$\Downarrow$

Organization of electron and ion streams

$\Downarrow$

Magnetic amplification

$\Downarrow$

Propagation of the electromagnetic structure

$\Downarrow$

Gradual decay through plasma relaxation.

This sequence provides a unified interpretation of several experimentally observed characteristics of lightning, including crackling preceding major discharges, stepped leader propagation, plasma heating, channel branching, and the finite lifetime of the discharge. Within the proposed model, these phenomena are not independent processes but different manifestations of a single self-organizing electromagnetic mechanism

11. Predictions

A physically meaningful model should not only provide a consistent interpretation of existing observations but also produce predictions that can be verified experimentally. The proposed SOET model leads to several qualitative and quantitative predictions that differ from those expected in conventional descriptions of lightning propagation.

11.1 Existence of a Self-Organizing Electromagnetic Structure

The principal prediction of the model is the existence of a localized electromagnetic structure propagating at the head of the lightning leader. This structure should possess a well-defined magnetic field, finite lifetime, and characteristic spatial extent. The propagating entity is predicted to represent an organized electromagnetic state rather than merely the advancing boundary of a conductive plasma channel.

11.2 Characteristic Length of SOET

The model predicts that SOET possesses a characteristic longitudinal dimension determined by the relaxation time of the organized plasma motion.

Its length should satisfy approximately

$$L_{\text{SOET}} \approx v_{\text{SOET}} \tau_{\text{rel}},$$

where

- v_{SOET} is the propagation velocity,
- τ_{rel} is the characteristic relaxation time of the organized electron-ion system.

The model therefore predicts that SOET should possess a finite characteristic length rather than extending along the entire lightning channel.

11.3 Critical Current

Not every impulsive current develops into a lightning discharge.

The model predicts the existence of a critical current

$$I_c,$$

below which the current pulse rapidly decays, and above which electromagnetic self-organization becomes possible.

Consequently, the probability of lightning initiation should increase rapidly once the local current exceeds the critical condition.

11.4 Correlation Between Crackling and Lightning Probability

Continuous crackling inside thunderstorms is interpreted as the repeated formation of impulsive current pulses that fail to reach the critical condition.

The model therefore predicts that increasing crackling activity should statistically precede the formation of major lightning discharges.

Rather than representing independent electrical events, crackling and lightning should form a continuous spectrum of the same physical process.

11.5 Magnetic Structure at the Leader Head

The strongest magnetic field is predicted to occur close to the propagating SOET rather than being uniformly distributed along the entire lightning channel.

Sensitive magnetic measurements should therefore detect a localized enhancement moving together with the leader head.

11.6 Plasma Temperature Distribution

The highest plasma temperatures are predicted to occur inside the active SOET region where counter-propagating electron and ion streams possess the largest relative velocities.

The already relaxed plasma behind the propagating structure should gradually cool as the organized charge streams disappear.

11.7 Electromagnetic Radiation

Since the electromagnetic structure continuously evolves while propagating, the model predicts that the strongest radio-frequency emission should originate primarily from the active SOET rather than uniformly from the entire lightning channel.

The temporal evolution of radio emission should therefore correlate with the growth and decay of the electromagnetic structure.

11.8 Stepped Propagation

The stepped propagation of negative lightning leaders is interpreted as the sequential formation of individual SOET structures.

Each propagation step corresponds to the successful formation and stabilization of a new self-organizing electromagnetic state.

The characteristic length of individual steps is therefore expected to correlate with the characteristic length of SOET.

11.9 Natural Termination of Lightning

The model predicts that lightning termination does not require the disappearance of the external electric field.

Instead, the discharge ceases when

$$v_e \approx v_i,$$

so that

$$J \to 0,$$

leading to the disappearance of the magnetic field sustaining SOET.

The lifetime of lightning is therefore predicted to depend primarily on the relaxation dynamics of the plasma rather than solely on the available electrostatic energy.

Summary of Predictions

The principal experimentally testable predictions of the proposed model are:

- existence of a localized propagating electromagnetic structure (SOET),
- existence of a critical current for electromagnetic self-organization,
- characteristic SOET length,
- localized magnetic-field enhancement near the leader head,
- maximum plasma temperature within the active SOET region,
- correlation between crackling intensity and lightning probability,
- correlation between radio emission and SOET propagation,
- lightning termination governed by plasma relaxation.

If future measurements confirm these predictions, the proposed model would provide a unified physical interpretation of lightning initiation, propagation, plasma heating, branching, and decay.

12. Discussion

The Self-Organizing Electromagnetic Tube (SOET) proposed in this work represents a working hypothesis intended to explain several experimentally observed characteristics of lightning within a unified physical framework. Rather than introducing new electromagnetic laws, the model investigates whether the collective interaction between electromagnetic fields and partially ionized plasma may produce a self-organizing propagating structure capable of sustaining lightning propagation.

A principal strength of the proposed model is that it links a number of apparently independent observations into a single physical mechanism. Continuous crackling preceding major lightning discharges, impulsive current formation, stepped leader propagation, strong magnetic fields, extremely high plasma temperatures, branching, and the finite lifetime of lightning channels are interpreted as different stages of the same self-organizing process.

The model also provides a natural explanation for the statistical character of lightning initiation. Thunderstorms continuously generate numerous impulsive electrical disturbances, yet only a very small fraction develops into a complete lightning discharge. Within the present hypothesis, this behaviour follows naturally from the existence of a critical condition required for electromagnetic self-organization.

Another attractive feature of the model is that it does not require the propagating structure to consist of a fixed collection of charged particles. Instead, SOET is interpreted as a dynamically maintained electromagnetic state. As the structure propagates, charged particles continuously enter and leave the organized region, while the electromagnetic organization itself remains preserved. In this respect, SOET resembles other propagating nonlinear structures in physics, where the pattern persists although its microscopic constituents are continuously replaced.

The proposed mechanism also offers an alternative interpretation of plasma heating. Rather than attributing the observed temperatures exclusively to Joule heating, the model suggests that energetic collisions between counter-propagating electron and ion streams may constitute an additional source of thermal energy. Whether this contribution is quantitatively significant remains an open question requiring detailed plasma simulations and comparison with experimental observations.

Several aspects of the proposed hypothesis require further investigation. The present work develops only the qualitative physical mechanism and introduces the concept of a critical transition leading to electromagnetic self-organization. A quantitative description of the stability of SOET, its characteristic dimensions, propagation velocity, lifetime, and energy balance remains to be developed. Such a description will require a self-consistent solution of Maxwell's equations coupled with the transport equations governing charged-particle motion in partially ionized plasma.

The model should also be regarded as experimentally falsifiable. The existence of a localized electromagnetic structure propagating together with the lightning leader, the predicted characteristic length of SOET, the correlation between crackling intensity and lightning initiation, and the predicted localization of the strongest magnetic fields near the leader head all represent observable consequences that may be tested by future high-speed optical, magnetic, and radio-frequency measurements. Failure to observe these predicted characteristics would require substantial revision or rejection of the proposed hypothesis.

Although the present study is restricted to atmospheric lightning, the underlying mechanism is not intrinsically limited to terrestrial thunderstorms. If SOET represents a general form of electromagnetic self-organization in partially ionized plasmas, analogous structures may occur in other plasma environments whenever three basic conditions are simultaneously satisfied:

- the presence of a partially ionized plasma,
- the generation of a sufficiently strong impulsive current,
- plasma conditions capable of sustaining electromagnetic self-organization.

Potential examples include volcanic plumes, dust storms, planetary atmospheres, and astrophysical plasmas. The present work does not claim that SOET has been identified in such environments. Rather, it suggests that the proposed mechanism may represent a more general physical process worthy of investigation beyond terrestrial lightning.

Finally, the proposed model should not be regarded as an alternative to classical electromagnetism. On the contrary, it assumes that Maxwell's equations remain valid throughout the entire process. The novelty lies in the hypothesis that the collective interaction between electromagnetic fields and partially ionized plasma may generate a dynamically stable propagating state whose properties differ qualitatively from those of an ordinary transient electrical discharge.

If future theoretical and experimental studies support this hypothesis, the concept of a Self-Organizing Electromagnetic Tube could provide a unified framework for understanding not only lightning propagation but also a broader class of self-organizing electromagnetic phenomena in plasmas.

13. Conclusions

This work has presented a new working hypothesis for the initiation and propagation of lightning based on the concept of a **Self-Organizing Electromagnetic Tube (SOET)**. The proposed model interprets lightning not merely as an electrical discharge through a conductive plasma channel, but as the propagation of a dynamically maintained electromagnetic structure continuously interacting with the surrounding partially ionized atmosphere.

According to the proposed mechanism, localized impulsive electric fields first generate short-lived current pulses within the thundercloud. Most of these pulses rapidly decay and correspond to the numerous transient electrical events observed as atmospheric crackling. Only those current pulses exceeding a critical condition evolve into self-organizing electromagnetic structures capable of sustaining their own propagation.

Within the proposed model, SOET continuously exchanges energy and momentum with the surrounding plasma. The different dynamical responses of electrons and positive ions produce counter-propagating charge streams whose temporary velocity difference generates the electric current required to maintain the surrounding magnetic field. This establishes a positive feedback process that enables the electromagnetic structure to propagate through the atmosphere.

The same interaction that produces the organized current also determines the finite lifetime of SOET. As collisions progressively equalize the average velocities of electrons and ions, the current decreases, the magnetic field weakens, and the electromagnetic structure naturally disappears. Lightning termination is therefore interpreted as the relaxation of a self-organized plasma system rather than the abrupt cessation of an externally driven discharge.

The proposed model provides a unified qualitative interpretation of several characteristic features of lightning, including impulsive initiation, atmospheric crackling, stepped leader propagation, intense magnetic fields, high plasma temperatures, branching, and the finite duration of lightning channels. These phenomena are interpreted as different manifestations of a single process of electromagnetic self-organization occurring within a partially ionized plasma.

An important feature of the hypothesis is that it remains directly testable. The existence of a localized propagating electromagnetic structure, a characteristic SOET length, a critical current for self-organization, localized magnetic-field enhancement near the leader head, and specific relationships between crackling activity and lightning initiation represent experimentally verifiable predictions. Future high-speed optical, magnetic, and radio-frequency observations should therefore be capable of confirming or refuting the proposed mechanism.

The present work should be regarded as a first step toward a quantitative theory of lightning based on electromagnetic self-organization. Further development will require a self-consistent mathematical description coupling Maxwell's equations with plasma transport equations and comparison with dedicated experimental measurements.

If confirmed experimentally, the proposed SOET mechanism would provide a unified physical framework for understanding lightning initiation, propagation, and decay as different stages of a single self-organizing electromagnetic process. More broadly, it would suggest that self-organizing electromagnetic structures may represent a fundamental dynamical mode of partially ionized plasmas extending beyond terrestrial lightning.

Appendix A – Dynamical Mathematical Model of SOET

A1. Fundamental Variables

The qualitative model developed in the main text may be expressed mathematically by introducing a small number of macroscopic variables describing the collective evolution of the Self-Organizing Electromagnetic Tube (SOET). Rather than following the trajectories of individual charged particles, the present formulation treats the plasma as a continuous dynamical system characterized by averaged quantities.

The principal variables are defined as follows.

Electron velocity

$$v_e(\mathbf{r},t)$$

Average drift velocity of electrons within the SOET.

Ion velocity

$$v_i(\mathbf{r},t)$$

Average drift velocity of positive ions within the SOET.

Velocity Difference

The average drift velocities of electrons and positive ions are therefore denoted by

$$v_e(\mathbf{r},t)$$

and

$$v_i(\mathbf{r},t),$$

respectively.

Since the two charge populations propagate in opposite directions, the relative drift velocity is defined as

$$w = v_i - v_e.$$

The variable w characterizes the dynamical asymmetry of the organized plasma. It will subsequently be shown that this quantity governs both the electric current generated by the counter-streaming charges and the relative velocity of electron-ion collisions.

Charge-carriers density

$$n(\mathbf{r},t)$$

Effective density of free charged particles participating in the organized plasma motion.

For simplicity, the first version of the model assumes

$$n_e \approx n_i = n,$$

where n_e and n_i denote the electron and ion number densities.

Electric current density

The organized current density is written as

$$J = en\Delta v.$$

This expression follows directly from the counter-propagating electron and ion streams described in the main text.

Magnetic field

$$B(\mathbf{r},t)$$

Average magnetic field generated by the organized current inside SOET.

Since the magnetic field is produced by the current,

$$B = \mathcal{F}(J),$$

where $\mathcal{F}$represents the relationship determined by Maxwell's equations. In the simplest approximation,

$$B \propto J.$$

Electromagnetic energy

$$U(t)$$

Total electromagnetic energy stored within SOET.

Plasma temperature

$$T(t)$$

Average plasma temperature inside the organized electromagnetic structure.

Relaxation time

$$\tau$$

Characteristic time during which collisions reduce the organized velocity difference between electrons and ions.

Propagation velocity

$$v_{\mathrm{SOET}}$$

Velocity of the propagating electromagnetic structure relative to the surrounding atmosphere.

Characteristic length

$$L_{\mathrm{SOET}}$$

Characteristic longitudinal dimension of SOET.

The present model assumes

$$L_{\mathrm{SOET}} \approx v_{\mathrm{SOET}}\tau.$$

Fundamental Dynamical Variables

Although several physical quantities appear in the model, its dynamics are governed primarily by two coupled variables:

$$\boxed{\Delta v = v_e - v_i}$$

and

$$\boxed{B.}$$

The velocity difference determines the organized electric current,

$$J = en\Delta v,$$

while the current generates the magnetic field. Conversely, the magnetic field organizes the plasma motion and thereby modifies the velocity difference. The entire evolution of SOET is therefore described as the mutual interaction between these two dynamical quantities.

The remaining variables, including plasma temperature, electromagnetic energy, conductivity, and the lifetime of SOET, are regarded as secondary quantities that follow from this coupled evolution.

A2. Formation of the Current

The organized electric current within SOET is not assumed to exist a priori. Instead, it develops naturally from the collective motion of electrons and positive ions interacting with the propagating electromagnetic structure.

The average drift velocities of electrons and ions are denoted by

$$v_e$$

and

$$v_i,$$

respectively.

The corresponding current density is given by the general expression

$$\mathbf{J} = en_i\mathbf{v}_i - en_e\mathbf{v}_e,$$

where

- e is the elementary charge,
- n_e and n_i are the number densities of electrons and ions.

For a quasi-neutral plasma,

$$n_e \approx n_i = n,$$

the current density becomes

$$\mathbf{J} = en(\mathbf{v}_i - \mathbf{v}_e).$$

Since the electron and ion streams propagate in opposite directions along the SOET axis, the organized current depends on the relative drift velocity introduced in Section A1,

$$w = v_i - v_e,$$

yielding

$$\boxed{J = enw.}$$

The quantity w therefore represents the primary dynamical variable governing current formation within SOET. An increase in the relative drift velocity immediately produces a proportional increase in the organized electric current.

An important consequence of this formulation is that the current is not generated by electrons alone. Both charge populations contribute simultaneously to the organized current. Because the electron stream and the ion stream move in opposite directions while carrying opposite electric charges, their contributions reinforce one another rather than cancel.

The resulting current is therefore determined by the collective organization of the plasma rather than by the motion of a single species. This constitutes one of the principal differences between the present SOET model and simplified descriptions in which only electron motion is considered.

A3. Magnetic Field

The organized electric current generated within SOET immediately produces a magnetic field according to Maxwell–Ampère's equation,

$$\nabla \times \mathbf{B} = \mu_0\mathbf{J} + \mu_0\varepsilon_0\frac{\partial \mathbf{E}}{\partial t}.$$

During the active stage of SOET, the characteristic time of the organized plasma motion is assumed to be much longer than the characteristic electromagnetic response time. In the first approximation, the displacement-current term may therefore be neglected, yielding

$$\nabla \times \mathbf{B} = \mu_0\mathbf{J}.$$

The magnetic field is thus determined directly by the organized current density derived in the previous section.

For an axisymmetric current channel, the magnetic field is predominantly toroidal around the SOET axis. The local field strength increases with increasing current and decreases with radial distance from the axis. In cylindrical coordinates, the first approximation is

$$B_\theta(r) = \frac{\mu_0 I(r)}{2\pi r},$$

where I(r) is the current enclosed within the radius r. (See Figure 1)

The present model assumes that this magnetic field is not merely a passive consequence of the current. Instead, it actively interacts with the surrounding plasma, organizing the motion of electrons and ions. This organized motion increases the current described in Section A2, thereby strengthening the magnetic field itself.

Consequently, the magnetic field performs a dual role:

- it is generated by the organized electric current;
- it simultaneously modifies the plasma dynamics responsible for that current.

The magnetic field therefore represents the coupling variable connecting the electromagnetic state of SOET with the collective motion of the surrounding plasma. This coupling constitutes the physical basis of the self-amplifying feedback mechanism developed in the following sections

A4. Plasma Organization

The previous sections established that the organized current generated within SOET produces a magnetic field according to Maxwell's equations. The present hypothesis assumes that this magnetic field, together with the motion of the electromagnetic structure, continuously modifies the surrounding plasma.

The proposed mechanism does not assume that the magnetic field directly accelerates charged particles along the direction of propagation. Instead, the magnetic field changes their trajectories and organizes their collective motion within the electromagnetic structure.

Because electrons and positive ions differ greatly in mass,

$$m_e \ll m_i,$$

their dynamical response is not identical. Electrons establish an organized current almost immediately after the impulsive electric field is created, whereas the ion current develops with a finite delay.

Consequently, the electron current

$$J_e(z,t)$$

and the ion current

$$J_i(z,t)$$

are generally neither equal nor perfectly synchronized in space and time.

The total organized current sustaining the magnetic field is therefore

$$J_{\mathrm{tot}} = J_e + J_i,$$

whereas the temporal and spatial asymmetry between the two currents is characterized by

$$J_{\mathrm{asym}} = J_e - J_i.$$

The present hypothesis assumes that this asymmetry plays a central role in the propagation of SOET. The magnetic field is maintained by the total organized current, while the delayed development of the ion current continuously shifts the region in which the electromagnetic structure is sustained.

As the ion current approaches the electron current,

$$J_i \to J_e,$$

the asymmetry decreases, reducing the ability of SOET to propagate further. At the same time, the total current may remain sufficiently large to maintain the magnetic field locally. Propagation and field generation are therefore governed by different combinations of the electron and ion currents.

A complete mathematical description of this process requires a self-consistent treatment of the momentum exchange between the electromagnetic structure, electrons, and ions. Such a formulation is beyond the scope of the present appendix and is left for future development.

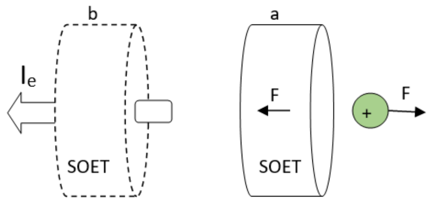

***Figure 3**: There is a repulsive force between the ions and the SOET. This force accelerates the ion (in the picture) to the right and the SOET to the left. The inertia of the SOET is not large, so the ion can easily move the SOET from point a to point b. There, however, there is a mass of fast electrons that emerge from the SOET and move in the direction of the strengthening of the SOET's magnetic field.*

Proposed mechanism of plasma organization inside the propagating Self-Organizing Electromagnetic Tube (SOET). As the electromagnetic structure advances through partially ionized plasma, electrons respond rapidly to the electromagnetic field, whereas the heavier positive ions accelerate more slowly. This temporary dynamical asymmetry produces counter-propagating charge streams whose combined motion generates the electric current sustaining the magnetic field. Continuous exchange of energy and momentum between SOET and the surrounding plasma establishes the positive feedback responsible for the propagation of the electromagnetic structure.

A5. Magnetic Amplification

The magnetic field of SOET is generated by the total organized current carried by electrons and positive ions. As defined in the previous section,

$$J_{\rm tot}(z,t) = J_e(z,t) + J_i(z,t),$$

where Je and Ji denote the magnitudes of the electron and ion contributions to the same conventional current direction.

For an approximately axisymmetric current distribution, the azimuthal magnetic field at radial distance r is determined by the enclosed current,

$$B_\varphi(r,z,t) = \frac{\mu_0 I_{\rm enc}(r,z,t)}{2\pi r}.$$

The enclosed current is obtained from the current density,

$$I_{\rm enc}(r,z,t) = \int_{A(r)} J_{\rm tot}(r',z,t)\, dA'.$$

Consequently, any increase in the total organized current produces a corresponding increase in the magnetic field surrounding the SOET axis.

The term *magnetic amplification* does not imply that the magnetic field independently creates energy or electric current. The field is amplified only when the interaction between SOET and the surrounding plasma produces an increase in the organized electron and ion currents. The energy required for this increase must arise from the exchange of energy and momentum between the electromagnetic structure and the charged particles.

The magnetic energy density is

$$u_B = \frac{B^2}{2\mu_0},$$

and the total magnetic energy contained within the SOET volume V_T is

$$U_B(t) = \int_{V_T} \frac{B^2}{2\mu_0}\, dV.$$

The evolution of the magnetic energy may therefore be written in the general form

$$\boxed{\frac{dU_B}{dt} = P_{\rm plasma\to B} - P_{\rm loss},}$$

where Pplasma→B is the power transferred from organized charged-particle motion into the magnetic field, and Ploss includes all mechanisms by which organized electromagnetic energy is converted into heat, radiation, random particle motion, or fields propagating away from SOET.

The power transferred from the plasma to the electromagnetic field cannot yet be expressed solely as a function of B. It depends on the spatial and temporal development of both charge streams,

$$P_{\text{plasma}\to\text{B}} = \mathcal{P}\left[J_e(z,t), J_i(z,t), B(z,t), X_T(t)\right],$$

where $X_T(t)$ denotes the position of SOET.

This dependence is important because the total current and the current asymmetry have different physical roles. The total current,

$$J_{\text{tot}} = J_e + J_i,$$

determines the magnetic-field strength, whereas

$$J_{\text{asym}} = J_e - J_i$$

characterizes the delayed development of the ion current relative to the electron current and is therefore associated with the propagation dynamics of SOET.

A strong magnetic field may still exist when

$$J_e \approx J_i,$$

because the two contributions reinforce the same conventional current. However, in this state,

$$J_{\text{asym}} \approx 0,$$

and the spatial–temporal asymmetry required for continued propagation is lost. The conditions for maintaining the magnetic field and for propagating SOET are therefore not identical.

For the first phenomenological description, magnetic amplification may be characterized by the dimensionless factor

$$R_B = \frac{P_{\text{plasma}\to\text{B}}}{P_{\text{loss}}}.$$

Three regimes are possible:

$$R_B < 1$$

corresponds to decreasing magnetic energy and decay of SOET;

$$R_B = 1$$

corresponds to approximate dynamic equilibrium;

$$R_B > 1$$

corresponds to increasing magnetic energy and amplification of the electromagnetic structure.

This factor does not yet constitute a complete stability criterion, because propagation also requires a sufficiently large current asymmetry. A propagating SOET must therefore satisfy two conceptually distinct conditions:

$$\boxed{R_B \geq 1}$$

for preservation or growth of its magnetic structure, and

$$\boxed{|J_{\text{asym}}| > J_{\text{asym,c}}}$$

for continued displacement of the structure into a newly formed electron-current region.

The critical asymmetry Jasym,c is introduced here only phenomenologically. Its physical value must ultimately be derived from the momentum balance between SOET, electrons, ions, and the surrounding neutral atmosphere.

Thus, magnetic amplification within the present model is not a direct action of the magnetic field upon itself. It is the result of organized plasma currents transferring energy into the electromagnetic structure. The magnetic field is sustained by the sum of the electron and ion currents, while the difference in their spatial and temporal development determines whether the SOET can continue to propagate.

A6. Energy Balance

The evolution of SOET is governed by a continuous exchange of energy between the electromagnetic field and the surrounding plasma. No energy is created within the electromagnetic structure itself. Instead, SOET continuously converts energy between different physical forms while interacting with the charged particles encountered during propagation.

The total energy of the system is written as

$$U_{\text{tot}} = U_E + U_B + U_e + U_i + U_{\text{th}},$$

where

- U_E is the electric-field energy,
- U_B is the magnetic-field energy,
- U_e is the organized kinetic energy of the electron stream,
- Ui is the organized kinetic energy of the ion stream,
- Uth is the thermal energy generated by collisions.

The electromagnetic energy is

$$U_{\text{EM}} = U_E + U_B.$$

The organized kinetic energies are

$$U_e = \frac{1}{2} m_e N_e v_e^2,$$

and

$$U_i = \frac{1}{2} m_i N_i v_i^2,$$

where Ne and Ni denote the numbers of electrons and ions participating in the organized plasma motion.

Although the electron mass is much smaller than the ion mass,

$$m_e \ll m_i,$$

both charge populations contribute to the total organized energy because the ion velocities are generally lower than the electron velocities.

During propagation, energy is continuously transferred between these components.

The principal energy pathways are

$$U_E \Longleftrightarrow U_B$$

through Maxwell's equations,

$$U_B \Longleftrightarrow U_e + U_i$$

through electromagnetic interaction with the plasma,

and

$$U_e + U_i \Longrightarrow U_{\text{th}}$$

through collisions between electrons, ions, and neutral particles.

Additional energy leaves the system through electromagnetic radiation,

$$U_{\text{rad}}.$$

The overall energy balance may therefore be written as

$$\boxed{\frac{dU_{\text{tot}}}{dt} = P_{\text{in}} - P_{\text{rad}},}$$

where

$$P_{\text{in}}$$

denotes the power transferred from the surrounding plasma into the organized electromagnetic structure, while

$$P_{\text{rad}}$$

represents all irreversible energy losses leaving the SOET.

The redistribution of energy inside SOET may therefore be summarized schematically as

$$U_E \Longleftrightarrow U_B \Longleftrightarrow (U_e + U_i) \Longrightarrow U_{\text{th}} \Longrightarrow U_{\text{rad}}.$$

Within the proposed model, lightning heating does not represent an independent process. It is the natural consequence of the continuous conversion of organized kinetic energy into random thermal motion through collisions among counter-propagating charged particles

A7. Stability

The stability of SOET cannot be characterized by a single condition. The preceding sections indicate that two physically distinct forms of stability must be distinguished:

1. **field stability**, describing whether the electromagnetic structure can maintain its magnetic energy;
2. **propagation stability**, describing whether the structure can continue moving into newly organized plasma.

A SOET may temporarily preserve a strong magnetic field without continuing to propagate. Conversely, a pronounced current asymmetry may produce a short displacement without supplying enough total current to maintain the electromagnetic structure. A stable propagating SOET therefore requires both conditions simultaneously.

A7.1 Magnetic stability

The magnetic field is maintained by the total organized current

$$J_{\text{tot}} = J_e + J_i.$$

As established in Section A5, the magnetic-energy balance may be written as

$$\frac{dU_B}{dt} = P_{\text{plasma}\to\text{B}} - P_{\text{loss}}.$$

It is useful to define the magnetic amplification factor

$$R_B = \frac{P_{\text{plasma}\to\text{B}}}{P_{\text{loss}}}.$$

The three possible regimes are

$$R_B < 1,$$

for which the magnetic energy decreases,

$$R_B = 1,$$

for which the magnetic energy remains approximately constant, and

$$R_B > 1,$$

for which the magnetic field is amplified.

The condition for magnetic stability is therefore

$$\boxed{R_B \geq 1.}$$

Equivalently,

$$\boxed{P_{\text{plasma}\to\text{B}} \geq P_{\text{loss}}.}$$

This condition determines whether SOET can preserve its electromagnetic structure, but it does not yet determine whether the structure propagates.

A7.2 Propagation stability

Propagation is associated with the spatial and temporal asymmetry between the electron and ion currents,

$$J_{\text{asym}} = J_e - J_i.$$

The electron current develops rapidly in the newly activated region, whereas the ion current responds with a delay because of the much larger ion inertia. This delay creates a region in front of the existing SOET in which the electron contribution is already established but the ion contribution remains smaller.

The current asymmetry must be sufficiently large to produce a non-zero transfer of momentum between the plasma and the electromagnetic structure. The corresponding propagation condition may be written phenomenologically as

$$\boxed{|J_{\mathrm{asym}}| > J_{\mathrm{asym,c}},}$$

where Jasym,c is the minimum asymmetry required to overcome momentum losses caused by collisions, deformation of the structure, and interaction with the neutral atmosphere.

A more general condition follows from the momentum balance,

$$\frac{dP_T}{dt} = F_{\mathrm{plasma}} - F_{\mathrm{resist}},$$

where

- PT is the momentum associated with SOET,
- Fplasma is the net reaction force exerted by the plasma,
- Fresist represents the effective resistance to propagation.

Continued propagation requires

$$\boxed{F_{\mathrm{plasma}} > F_{\mathrm{resist}}.}$$

For approximately uniform propagation,

$$F_{\mathrm{plasma}} \approx F_{\mathrm{resist}},$$

and the SOET velocity remains approximately constant.

A7.3 Combined stability condition

A stable propagating SOET must satisfy both

$$R_B \geq 1$$

and

$$|J_{\mathrm{asym}}| > J_{\mathrm{asym,c}}.$$

These two requirements may be combined schematically as

$$\boxed{\mathcal{S} = \mathcal{S}_B \mathcal{S}_P > 1,}$$

where

$$\mathcal{S}_B = \frac{P_{\mathrm{plasma}\to\mathrm{B}}}{P_{\mathrm{loss}}}$$

describes magnetic stability, while

$$\mathcal{S}_P = \frac{|F_{\mathrm{plasma}}|}{|F_{\mathrm{resist}}|}$$

describes propagation stability.

Thus,

$$\mathcal{S}_B < 1$$

causes the electromagnetic structure to decay regardless of the current asymmetry, whereas

$$\mathcal{S}_P < 1$$

causes propagation to stop even if a residual magnetic field remains temporarily present.

The four possible regimes are therefore:

$\mathcal{S}_B$	$\mathcal{S}_P$	Behaviour
< 1	< 1	rapid decay
≥ 1	< 1	magnetically sustained but non-propagating state
< 1	≥ 1	short displacement followed by decay
≥ 1	≥ 1	stable propagation

A7.4 Dynamic equilibrium

Stable propagation does not imply a static structure. SOET remains a strongly dynamical system in which energy and momentum are continuously exchanged among the electromagnetic field, electrons, ions, neutral particles, heat, and radiation.

For approximately uniform propagation, the average balances satisfy

$$\frac{dU_{\mathrm{SOET}}}{dt} \approx 0$$

and

$$\frac{dP_T}{dt} \approx 0.$$

These conditions imply

$$P_{\mathrm{in}} \approx P_{\mathrm{loss}}$$

and

$$\frac{dP_T}{dt} \approx 0.$$

The structure therefore persists not because its internal state remains unchanged, but because the continuous gains and losses remain approximately balanced.

A7.5 Loss of stability

SOET becomes unstable when either of the two balances fails.

If the total organized current decreases,

$$J_{\text{tot}} \downarrow,$$

then

$$B \downarrow, \qquad U_B \downarrow, \qquad R_B < 1,$$

and the electromagnetic structure decays.

If the delayed ion current approaches the electron current,

$$J_i \to J_e,$$

then

$$J_{\text{asym}} \to 0,$$

the net momentum-transfer asymmetry disappears, and propagation stops even though the two current contributions may still maintain a temporary magnetic field.

The model therefore predicts two distinct stages of termination:

$$\text{loss of propagation asymmetry}$$

followed by

$$\text{loss of magnetic-field support.}$$

This distinction is important because the cessation of SOET propagation need not coincide exactly with the disappearance of the current or magnetic field.

A7.6 Present limitation

The critical quantities

$$J_{\text{asym,c}}, \qquad F_{\text{resist}}, \qquad P_{\text{plasma}\to\text{B}}, \qquad P_{\text{loss}}$$

have not yet been derived from microscopic plasma parameters. Their determination requires a coupled treatment of Maxwell's equations, electron and ion momentum equations, collision terms, and the momentum carried by the electromagnetic field.

The present stability analysis should therefore be regarded as a general framework rather than a completed quantitative criterion. Its principal result is that SOET stability requires two independent balances:

Total current maintains the magnetic structure

while

electron–ion current asymmetry maintains its propagation.

This separation between magnetic stability and propagation stability is the central mathematical conclusion of the first SOET stability model.

A8. Characteristic Length

One of the principal predictions of the proposed SOET model is that the electromagnetic structure possesses a finite characteristic length. This length is not prescribed a priori but emerges naturally from the balance between plasma organization at the leading edge and plasma relaxation behind the propagating structure.

The front of SOET continuously encounters fresh partially ionized plasma. New electrons rapidly establish an organized current, while the corresponding ion current develops with a finite delay. Simultaneously, in the rear part of the structure, collisions progressively reduce the asymmetry between the electron and ion currents, causing the organized current to decay.

The longitudinal dimension of SOET is therefore determined by two competing processes:

- formation of new organized current at the leading edge,
- relaxation of previously organized plasma at the trailing edge.

If the propagation velocity is approximately constant,

$$v_{\mathrm{SOET}},$$

and the characteristic relaxation time is

$$\tau_{\mathrm{rel}},$$

the first approximation for the characteristic length is

$$\boxed{L_{\mathrm{SOET}} \approx v_{\mathrm{SOET}} \tau_{\mathrm{rel}}.}$$

This expression should not be regarded as an exact solution but as the lowest-order approximation obtained when both the propagation velocity and the relaxation time remain approximately constant.

More generally,

$$L_{\mathrm{SOET}} = \int_{t_0}^{t_0+\tau_{\mathrm{rel}}} v_{\mathrm{SOET}}(t)\, dt,$$

allowing for variations of the propagation velocity during the evolution of the structure.

The relaxation time itself depends on several plasma properties,

$$\tau_{\mathrm{rel}} = f(n, T, \nu_{\mathrm{coll}}, x_i),$$

where

- n is the charged-particle density,
- T is the plasma temperature,
- ν_{coll} is the effective collision frequency,
- xi is the ionization fraction.

Consequently, the characteristic length is not expected to be universal but to vary with the local properties of the thundercloud plasma.

Within the present model, propagation ceases when the trailing part of SOET loses its organized current faster than the leading edge can establish a new one. The limiting condition may therefore be written qualitatively as

$$\tau_{\mathrm{form}} < \tau_{\mathrm{rel}},$$

where

τ_{form} denotes the characteristic time required to establish a new organized current at the leading edge.

If

$$\tau_{\mathrm{form}} > \tau_{\mathrm{rel}},$$

the SOET reaches its maximum sustainable length.

If

$$\tau_{\mathrm{form}} > \tau_{\mathrm{rel}},$$

the organized region contracts and the electromagnetic structure ultimately disappears.

The characteristic length is therefore interpreted not as a purely geometrical quantity but as the spatial manifestation of the dynamical balance between plasma organization and plasma relaxation.