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# The Plasma Nature of Lightning Channel by Correlating the EM Fields Generated by Lightning and Its Optical Spectrum

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**ABSTRACT:** The lightning channel is a rapidly evolving transient plasma that radiates intense electromagnetic (EM) fields and emits broadband optical radiation. This paper presents a theoretical and experimental investigation into the correlation between electromagnetic fields generated during lightning events and the corresponding optical spectra observed during various phases of the discharge. Using advanced EM field modelling and high-speed optical spectroscopy, we demonstrate that key plasma parameters such as temperature, electron density, and ionization state can be inferred from combined electromagnetic-optical datasets. This multidisciplinary analysis not only reveals the underlying physical characteristics of the lightning channel but also provides insights for future atmospheric diagnostics, lightning modelling, and protective technologies.

## 1. INTRODUCTION

Lightning, a transient atmospheric electrical discharge, has long fascinated and challenged scientists due to its immense energy, complex structure, and wide-ranging effects on human systems and natural environments. At the core of this phenomenon there is the lightning channel, a rapidly evolving plasma conduit that supports high-amplitude current pulses and emits a wide spectrum of electromagnetic (EM) and optical radiation. Research over the past several decades has made significant progress in characterizing various aspects of lightning, including the generation of EM fields, the plasma characteristics of the channel, and the optical emissions produced during different lightning phases. However, a holistic understanding that correlates these observables to decode the physical nature of the lightning channel remains incomplete.

The EM fields associated with lightning events have been extensively studied, particularly in the context of their temporal and spatial distributions and their implications for lightning detection and protection systems. It is well established that lightning generates intense electric and magnetic fields that span a wide frequency range from a few Hz to over 100 MHz. These fields, originating from time-varying lightning currents, can be broadly categorized into near-field (electrostatic), intermediate-field (inductive), and far-field (radiative) components. Notably, high-frequency transients are often associated with leader steps and fast return strokes [1–3]. The temporal characteristics of these EM fields provide insights into the current waveforms propagating along the channel, thus serving as indirect probes of channel conductivity and geometry.

Simultaneously, the lightning channel itself functions as a high-temperature, high-density plasma. This plasma state arises due to the intense heating caused by Joule dissipation of the lightning current, which raises the channel temperature to values between 20,000 K and 30,000 K within microseconds [4]. The channel plasma is partially ionized and exhibits strong gradients in temperature, pressure, and composition. These conditions influence the electrical conductivity, electromagnetic wave propagation characteristics, and overall energy dissipation dynamics of the channel. Parameters such as electron density, electron temperature, Debye length, and plasma frequency define the response of this transient plasma to external and self-generated EM fields [5–7]. However, in situ diagnostics of such rapidly evolving plasmas remain a formidable challenge due to the hostile and transient nature of the discharge.

To complement EM observations, optical spectroscopy has emerged as a valuable diagnostic technique to probe the thermodynamic and compositional characteristics of the lightning channel. Optical emissions during lightning originate from radiative transitions in atomic and molecular species such as N, O, N2+, and O2. Different phases of the discharge, stepped leader, return stroke, continuing current, and M-components, produce distinct spectral features. For instance, the return stroke is typically associated with a broadband continuum and discrete atomic lines, whereas the stepped leader often emits weak, sporadic lines from neutral species [8–10]. Spectroscopic measurements can yield electron temperature through Boltzmann analysis and electron density via Stark broadening, thereby offering direct plasma diagnostics.

Despite substantial progress in these three domains, EM field measurements, plasma modelling, and optical spectroscopy, the integration of these methodologies remains underdeveloped. Existing studies often treat EM and optical data as isolated observations, leading to a fragmented understanding of the lightning channel. A few recent investigations have hinted at the value of synchronously correlating optical and EM data. However, systematic studies that use high-resolution

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time-synchronized datasets to explore the causality and interdependence between EM signals and optical emissions are scarce [11]. Such a correlation is critical not only for refining theoretical models of lightning but also for improving practical applications such as early warning systems, EM interference mitigation, and atmospheric plasma modelling.

The objective of this study is to bridge this methodological gap by conducting a comprehensive correlation analysis between electromagnetic field signals and optical spectra recorded during lightning discharges. Our central hypothesis is that the temporal and spectral characteristics of EM fields can be linked with specific optical features to extract deeper insights into the lightning channel's plasma dynamics. We employ a combination of broadband EM field sensors and high-speed optical spectrometers, synchronized to within microsecond accuracy, to record and analyse data from natural and triggered lightning events in two regions with high lightning flash density.

This paper aims to contribute to the state of the art in the following ways:

- Provide a theoretical foundation linking EM field theory with plasma physics and radiative emission mechanisms.
- Present an experimental methodology for synchronous data acquisition and interpretation.
- Demonstrate how combined data can reveal plasma parameters such as temperature, density, and conductivity evolution.
- Offer recommendations for future research and applications based on our findings.

Through this integrated analysis, we seek to enhance the understanding of lightning as a multi-modal physical process and provide a platform for advanced diagnostics in atmospheric electricity research.

## 2. THEORETICAL BACKGROUND

### 2.1. Electromagnetic Fields Generated by Lightning

The electromagnetic (EM) fields produced by lightning are governed by transient charge movement and current flow in a highly conductive and evolving plasma channel. The theoretical modelling of these fields typically involves solving time-domain radiation equations derived from Maxwell's framework, adapted to model the transient current profiles within the lightning channel [12, 13].

For a vertically oriented lightning return stroke current, the radiation field components at an observation point located at distance $R$ and elevation angle $\theta$ can be approximated in the far-field domain using the electric and magnetic field expressions below.

$$E(\theta, R, t) = \frac{\mu_0}{4\pi}\frac{\sin\theta}{R}\frac{\partial I(t_r)}{\partial t},$$

$$B(\theta, R, t) = \frac{\mu_0}{4\pi}\frac{\sin\theta}{R}\frac{I(t_r)}{c} \quad (1)$$

where $t_r$ represents the retarded time. These expressions account for the radiation field component (proportional to), which dominates at distances several kilometres from the source [14, 15].

In the near-field (electrostatic and induction) regions, more comprehensive models are necessary. The expressions for the vertical electric field ($E_z$) and azimuthal magnetic field ($H_\phi$) for an idealized return stroke channel can be derived via numerical integration of the current distribution along the channel, as shown by Cooray's integral expressions [16].

$$E_z(r,t) = \frac{1}{2\pi\epsilon_0}\int_0^L\left[\frac{\rho\left(z',t_r\right)}{\left(r^2+z^2\right)^{3/2}} + \frac{1}{C^2}\frac{\partial^2 I\left(z',t_r\right)}{\partial t^2} \cdot \frac{z'}{\left(r^2+z^2\right)^{3/2}}\right]dz' \quad (2)$$

$$H_\emptyset(r,t) = \frac{1}{4\pi}\int_0^L\left[\frac{1}{c}\frac{\partial I\left(z',t_r\right)}{\partial t}\cdot\frac{r}{\left(r^2+z^2\right)^{3/2}}\right]dz' \quad (3)$$

$$r = \sqrt{\left(z-z'\right)^2+\rho^2}$$

where

$\rho$: radial distance from lightning channel to observation point.

$z$: height of observation point.

$z'$: variable height along the channel (integration variable).

$r$: Distance from source point (0, 0, $z'$) to observation point ($\rho$, 0, $z$).

$L$: length of the lightning channel.

$t_r = (t - r/c)$: Retarded time.

$I(z', t - r/c)$: current at the variable height of concern at the retarded time.

These formulations capture the distributed nature of lightning current, considering both quasi-electrostatic and radiation contributions. However, they require accurate knowledge of the current waveform and channel geometry, which remain challenging in real-world settings.

Recent computational models have incorporated the transmission line with exponential decay (MTLE) approach to approximate return stroke currents and evaluate EM fields at various ranges [17]. Despite their practicality, such models idealize the channel and ignore complex branching, tortuosity, and time-varying conductivity that significantly influence actual field strengths and waveforms.

The plasma in a lightning channel is governed by rapid Joule heating, leading to temperatures exceeding 30,000 K. Under these conditions, the ionization of nitrogen and oxygen occurs extensively, and the plasma transitions into a partially ionized state with time-varying conductivity [18]. The electron number density ($n_e$) typically reaches values in the range of $10^{17}$

to $10^{18}\,\mathrm{m}^{-3}$, resulting in plasma frequencies ($\omega_p$) in the GHz regime.

$$\omega_p = \sqrt{\frac{n_e e^2}{m_e \varepsilon_0}} \tag{4}$$

At such frequencies, EM wave propagation within the channel becomes dispersive, and wave reflection or absorption can occur, particularly for HF components. This complicates the correlation of externally measured EM fields with internal channel dynamics [19].

Runaway electron processes also invoke relativistic considerations. The relativistic runaway electron avalanche (RREA) model describes how high-energy electrons, accelerated by electric fields exceeding a critical value, can initiate breakdown and emit X-ray and gamma-ray bursts [20]. These emissions, known as terrestrial gamma-ray flashes (TGFs), have been detected from space and coincide with early lightning activity, suggesting that relativistic effects are integral to lightning initiation, though their coupling to main stroke EM fields remains speculative [21].

Although EM field theory related to lightning sciences is well established, several limitations persist in its application to lightning:

(a) Dynamic channel properties: Most models assume stationary current distributions and constant conductivity. In reality, the lightning channel evolves rapidly in geometry and plasma composition.

(b) Radiation source ambiguity: Precise localization of radiation sources along the channel is difficult due to overlapping emissions from multiple channel sections.

(c) Plasma feedback effects: Interaction between EM fields and the evolving plasma (e.g., self-induced conductivity enhancement) is often neglected.

(d) Limited spectral range: Many EM field sensors operate below 30 MHz, missing higher-frequency content critical for capturing leader-step formation and breakdown details [22].

Addressing these issues requires integrated multi-physics simulations, where plasma kinetics, radiative transport, and field equations are solved concurrently. Such simulations remain computationally intensive but have recently gained traction using GPU-accelerated finite-difference time-domain (FDTD) solvers [23].

This work aims to provide a path forward by correlating well-resolved EM field measurements with optical spectral data across the various phases of lightning evolution, thereby revealing the physical conditions and transitions within the lightning channel in both time and space.

### 2.2. Plasma Physics of the Lightning Channel

The lightning channel is a transient, non-equilibrium plasma exhibiting extreme gradients in temperature, pressure, and ionization. Its complex structure arises due to time-dependent energy deposition by impulsive electric currents, rendering it an ideal subject for plasma diagnostics. Understanding the plasma nature of lightning is crucial not only for accurate electromagnetic modelling but also for deriving atmospheric parameters and assessing lightning-induced chemical transformations.

The evolution of the channel is characterized by a rapid Joule heating process initiated by an impulsive current, typically 10–100 kA, with rise times in the microsecond range. This rapid energy input causes the gas temperature to rise above 30,000 K within microseconds, leading to complete or near-complete ionization of air constituents (primarily nitrogen and oxygen). Consequently, the channel becomes a partially ionized plasma with electron densities on the order of $10^{18}\,\mathrm{m}^{-3}$, which determine its conductivity, plasma frequency, and electromagnetic wave interaction properties [24, 25].

The governing equations of plasma dynamics in this context based on the two-fluid model are given below.

$$\frac{\partial n_e}{\partial t} + \nabla \cdot (n_e V_e) = S_i - S_r \tag{5}$$

$$\frac{dV_e}{dt} = \frac{-eE}{m_e} - v_{en} V_e \tag{6}$$

Here, $\nu_e$ is the electron velocity. $S_i$ and $S_r$ are the ionization and recombination source terms, respectively, and $v_{en}$ is the electron-neutral collision frequency. These formulations are highly dependent on local electric field **E**, which varies dynamically along the lightning channel. High collision frequencies ($> 10^{12}$ Hz) dominate the initial phase, with relaxation times of the order of nanoseconds [26].

Additionally, the Saha equation given below is often employed to estimate ionization levels at thermal equilibrium.

$$\frac{n_e n_i}{n_0} = \left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} \exp\left(-\frac{E_i}{kT}\right) \tag{7}$$

where $n_i$ and $n_0$ are the ion and neutral atom densities; $E_i$ is the ionization energy; $T$ is the plasma temperature; and $h$ is the Planck's constant. In the case of lightning, departures from thermal equilibrium are substantial, and a local thermodynamic equilibrium (LTE) assumption holds only during the peak of the return stroke phase [27].

Moreover, the electrical conductivity of the channel, critical for EM field computation, can be modelled by the following equation.

$$\sigma = \frac{n_e e^2}{m_e v_{en}} \tag{8}$$

Values of $\sigma$ typically range from $10^3$ to $10^4$ S/m, consistent with plasma resistivities used in transmission line return stroke models. These high conductivities suggest that the channel can be approximated as a nearly perfect conductor during early breakdown and return stroke phases, although local deviations exist due to recombination and expansion [28].

From a macroscopic viewpoint, shockwaves and hydrodynamic expansions follow the thermally driven ionization phase. The interaction between plasma dynamics and pressure gradients leads to channel widening, optical radiation, and subsequent cooling and re-neutralization. Simultaneously, emissions of electromagnetic and acoustic energy take place. Advanced plasma simulations, such as those using Particle-In-Cell (PIC) and Magneto-Hydrodynamics (MHD) codes, have attempted to resolve these multi-physics phenomena but remain computationally intensive [29, 30].

Emerging plasma phenomena such as sprite-like discharges, streamer-to-leader transitions, and attachment processes are areas with open theoretical questions. The key unknowns include;

(a) The transition criteria from cold streamer corona to hot leader plasma.
(b) Temporal resolution of plasma conductivity and its impact on EM wave generation.
(c) Nonlinear feedback between EM fields and ionization rates.

### 2.3. Optical Spectrum of Lightning

The optical spectrum of lightning serves as a critical diagnostic tool to probe the state and evolution of the plasma. Emission lines originate from excited neutral atoms, ions, and molecular bands of nitrogen and oxygen. Broadband continuum emission is also present during the hottest phases of the discharge, especially in the return stroke [31].

Spectroscopic analysis has revealed that the spectrum typically consists of:

(a) N I and N II lines (500–900 nm).
(b) I lines (near 777 nm and 845 nm).
(c) CN violet and red bands in stepped leaders.
(d) $H_\alpha$ at 656.3 nm, indicating the presence of water vapour.

Spectral intensities and line broadening inform on the temperature, electron density, and pressure in the channel. The Stark broadening of N II lines is a well-accepted method for estimating electron density, while Boltzmann plots of line intensities yield excitation temperatures [32, 33].

The lightning channel emissions vary significantly across the discharge phases. Identification of the below emissions is done by comparing observed line positions and intensities with standard atomic databases such as the NIST Atomic Spectra Database.

(a) Stepped leader phase: Emissions from atomic nitrogen and oxygen. Weak and sporadic.
(b) Return stroke phase: Bright continuum with strong lines such as O I (777 nm), N II, and N2+ first negative bands.
(c) Continuing current: Sustained low-energy emissions resembling black-body radiation.
(d) M-components/K-changes: Transient spectral features, occasionally showing ionized metallic species.

Recent observations using high-speed spectrometers (e.g., 10,000 fps with nanometer-scale spectral resolution) have provided temporally resolved spectra during dart leader-return stroke cycles. These studies show a rapid rise in continuum radiation followed by atomic line emission decay, suggesting a non-equilibrium transition during cooling phases [34].

Moreover, spectral signatures vary among intra-cloud (IC), cloud-to-ground (CG), and positive CG discharges. IC discharges show broader spectra with higher molecular content, while CG events exhibit sharp atomic transitions. These variations provide opportunities to classify lightning types remotely through spectral fingerprints [35].

In a nutshell, spectroscopy is a critical diagnostic technique in lightning research, enabling the estimation of fundamental plasma parameters such as temperature, electron density, ionization state, and chemical composition of the lightning channel. Given that lightning plasmas emit strong, broadband optical radiation across UV, visible, and near-infrared bands, the spectroscopic signatures captured from these emissions can be used to infer the internal state of the channel. The methodology leverages both emission line diagnostics and continuum radiation analysis. Below are the core physical quantities that can be determined:

#### 2.3.1. Electron temperature ($T_e$)

The electron (or excitation) temperature can be determined using the Boltzmann plot method based on the relative intensities of spectral lines emitted from different energy levels of the same species (usually neutral or singly ionized atoms):

$$\ln\left(\frac{I_{ul}\lambda}{g_u A_{ul}}\right) = -\frac{E_u}{kT_e} + \text{constant} \tag{9}$$

where:

$I_{ul}$: intensity of the emission line corresponding to the transition from upper level uuu to lower level lll,
$\lambda$: wavelength of the emission line,
$g_u$: statistical weight of the upper level,
$A_{ul}$: Einstein coefficient of spontaneous emission,
$E_u$: energy of the upper level,
$k$: Boltzmann constant,
$T_e$: electron temperature.

A plot of the logarithmic left-hand term against $E_u$ yields a straight line whose slope is proportional to $-1/kT_e$. For lightning channels, reported excitation temperatures typically lie in the range of 20,000 to 35,000 K during the peak current phase [25, 31].

#### 2.3.2. Electron Density ($n_e$)

The Stark broadening of spectral lines, particularly from hydrogen and ionized nitrogen (e.g., N II at 500.5 nm), is a robust diagnostic for electron density. The width $\Delta\lambda_{1/2}$ of the emission line is directly related to electron density via empirical or theoretical calibration:

$$\Delta\lambda_{1/2} \approx 2w = 10^{-16} n_e^{2/3} \tag{10}$$

where:

$\Delta\lambda_{1/2}$: full width at half maximum (FWHM) of the Stark-broadened line,
$n_e$: electron density ($\text{cm}^3$).

The analysis assumes a Lorentzian profile under Stark broadening dominance. For lightning, electron densities have been observed in the range of $10^{17}$ to $10^{18}\,\text{cm}^{-3}$ during the return stroke [32, 36].

#### 2.3.3. Ionization State and Degree of Ionization

Eq. (7) (Saha Equation) given previously can be applied in approximate LTE conditions to estimate the degree of ionization.

While this model may not strictly hold under the highly transient and non-LTE conditions of early lightning stages, it offers a useful estimation under quasi-equilibrium states in the mature channel.

Despite above above-discussed progress, limitations remain in the following areas.

(a) Atmospheric scattering and absorption can distort spectral profiles.
(b) Saturation of detectors during return stroke hinders accurate measurement.
(c) Line blending in dense plasma regimes complicates line identification.

The future of lightning spectroscopy lies in the fusion of EM and optical measurements. Coordinated campaigns employing very high frequency (VHF) interferometers, electric field mills, and spectrometers are essential for unraveling the full physics of lightning. Additionally, the deployment of AI-based pattern recognition in spectral datasets may enhance classification and retrieval of plasma parameters [33].

## 3. CORRELATION BETWEEN SPECTRAL OBSERVATION AND COMPOSITION OF PLASMA

Time-resolved spectroscopy has proven instrumental in unveiling the transient physical characteristics of lightning channels with microsecond to sub-microsecond temporal resolution [8, 32, 37, 38]. These spectral emissions are intricately linked to the underlying plasma dynamics, including temperature evolution, electron density variation, and ionization states of constituent species.

Despite the wealth of spectral data, a significant knowledge gap remains in systematically deriving the time-correlated plasma composition from these emissions. We focus on interpreting lightning-generated optical spectra to infer the plasma characteristics at distinct discharge phases. By integrating theoretical models, such as Boltzmann population distribution, Stark broadening, and Saha ionization equilibrium, with experimental observations, we present a coherent correlation between spectral line evolution and the thermodynamic state of the plasma [38].

This approach facilitates the characterization of the lightning plasma with greater precision, offering a valuable tool for validating numerical models and improving lightning detection and classification systems.

### 3.1. Plasma Diagnostic Principles from Spectroscopy

The light emitted from the lightning channel arises due to atomic and molecular transitions, which can be spectrally resolved to determine plasma properties. The population of excited energy levels follows Boltzmann statistics under LTE (local thermodynamic equilibrium) as given in Equation (11).

$$\frac{N_u(t)}{N(t)} = \frac{g_u}{Z(T_e(t))}\exp\left(-\frac{E_u}{kT_e(t)}\right) \tag{11}$$

where:

$g_u$: statistical weight of the upper level,
$E_u$: excitation energy,
$Z(T_c)$: partition function,
$T_e$: electron temperature,
$N(t)$: total population of species.

Derived from Equation (9), the spectral line intensity, $I(\lambda, t)$, at time $t$ is given by

$$I(\lambda, t) = \frac{hc}{4\pi\lambda}A_{ul}N_u(t) \tag{12}$$

Combining the above equations, we obtain

$$I(\lambda, t) \propto \frac{g_u A_{ul}}{Z(T_e(t))}\exp\left(-\frac{E_u}{kT_e(t)}\right)N(t) \tag{13}$$

Ionization state distributions are determined using Equation (14), which is a derivation from Equation (7).

$$\frac{n_{i+1}n_e}{n_i} = \left(\frac{2\pi m_e kT_e}{h^2}\right)^{3/2}\frac{2g_{i+1}}{g_i}\exp\left(-\frac{\Delta E_i}{kT_e}\right) \tag{14}$$

Electron density, $n_e$, is obtained via Stark broadening analysis following Equation (10);

$$\Delta\lambda_{\text{Stark}} = 2w\left(\frac{n_e}{10^{16}}\right)\ [\text{nm}] \tag{15}$$

where $\omega$ is the electron-impact width coefficient.

These derivations allow the inference of $T_e$ and $n_e$ ionization fractions directly from observed emission line profiles.

### 3.2. Experimental Observations and Derived Plasma Composition

The fundamental correlation arises because electromagnetic emissions (particularly in the LF/VLF and ULF range) are generated by the rapid acceleration of charges, primarily electrons, during leader progression and return stroke phases, while optical emissions originate from electronic transitions in ionized and excited atoms and molecules, induced by the same energy input. The strong logical correlation between spectral emissions and plasma state allows time-resolved plasma characterization of lightning as below.

(a) The intensity and spectrum of optical emissions are related to local current density, channel temperature, and degree of ionization, which also determine EM field strength.

(b) Return stroke currents > 30 kA is typically associated with bright optical flashes and high electric field peaks [25, 31].
(c) Stepped leaders emit weaker optical radiation (primarily N2 second positive system) but are clearly detectable in VLF/LF EMF as discrete pulses [34].

Each spectral phase reveals the thermodynamic fingerprint of the evolving discharge.

(a) Emission line species and intensities map to chemical composition and excitation temperature.
(b) Line broadening, especially Stark, informs about electron density.
(c) Molecular emissions in early and late phases highlight cooler, chemically reactive plasma.
(d) Ionized atomic lines during return strokes are indicative of fully developed plasma, with maximum energy deposition.

Such analysis also supports model calibration for lightning simulations, enabling improved understanding of energy transfer, channel dynamics, and associated electromagnetic fields.

The lightning channel emits light due to collisional excitation of atoms and ions, followed by radiative de-excitation. Numerous studies using high-speed imaging spectrometers have recorded these lightning spectra with microsecond resolution [24, 29, 34, 39–41]. Each spectral line corresponds to a specific atomic or ionic transition, allowing the identification of chemical species and physical parameters such as:

(a) Electron temperature ($T_e$): via Boltzmann plot method (Equations (9) and (11)).
(b) Electron density ($n_e$): via Stark broadening of spectral lines.
(c) Ionization state: via Saha equation in approximate LTE conditions (Equations (7) and (14)).
(d) Species abundance: via line intensity ratios and comparison with standard emissivity models.

Thus, key emission lines and molecular bands have been identified, enabling robust plasma diagnostics. Table 1 summarizes the derived plasma composition at various temporal phases of the lightning discharge.

## 4. INTERPRETATION AND SIGNIFICANCE OF OUTCOMES

The spectroscopic data in Table 1 reveal a clear transition in plasma state across the lightning discharge timeline:

**TABLE 1**. Time-correlated spectral observations and plasma characteristics.

| Lightning Phase | Dominant Spectral Features | Estimated Plasma Parameters | Simultaneous EM Signature | Interpretation & Correlation Insight |
|---|---|---|---|---|
| **Initial Breakdown / Stepped Leader** | $N_2$ Second Positive System (337.1 nm, 357.6 nm), $N_2^+$ First Negative Band (391.4 nm) | $T_e \approx$ 5000–8000 K; $n_e \approx 10^{13}$–$10^{14}$ cm$^{-3}$ | Discrete VLF/LF pulses (~10–100 µs apart) | Weakly ionized leader steps; each optical pulse matches an EM pulse; intermittent heating and localized ionization. |
| **Dart Leader (Reilluminated Channel)** | N II (500–700 nm), faint Hα, O I (777 nm) lines | $T_e \approx$ 10,000–15,000 K; $n_e \approx 10^{14}$–$10^{15}$ cm$^{-3}$ | Smooth rising E-field ramp (kV/m range) | More continuous ionization and heating; increasing plasma conductivity; buildup to return stroke. |
| **Return Stroke** | Bright Hα (656.3 nm), N I multiplets, O I lines, continuum radiation (400–700 nm) | $T_e \approx$ 25,000–35,000 K; $n_e \approx 10^{16}$–$10^{17}$ cm$^{-3}$ | Sharp E-field pulse (>10 kV/m at 10 km) | Peak current and energy deposition; intense optical flash coinciding with peak EM radiation; plasma becomes highly ionized. |
| **M Components / Secondary Surges** | N II, O II, weak continuum | $T_e \approx$ 15,000–20,000 K; $n_e \approx 10^{15}$–$10^{16}$ cm$^{-3}$ | Intermediate-magnitude EM peaks, less sharp than return stroke | Re-illumination of channel with secondary currents; partial re-ionization of plasma. |
| **Continuing Current** | CN Violet (388.3 nm), OH (A-X) bands, $C_2$ Swan bands | $T_e \approx$ 7000–10,000 K; $n_e \approx 10^{13}$–$10^{14}$ cm$^{-3}$ | Low-amplitude, broadband EM radiation; quasi-steady field | Cooling plasma; molecular recombination dominates; sustained channel conductivity with weak EM field. |
| **Terminal Phase / Recombination** | Weak N I, CN, and OH emissions; fading continuum | $T_e \approx$ 4000–7000 K; $n_e \approx 10^{12}$–$10^{13}$ cm$^{-3}$ | Minimal EM activity; field decay phase | Radiative and conductive cooling; recombination of plasma into neutral and molecular species; EM silence corresponds with optical fade-out. |

(a) Stepped leader phase: The presence of weak neutral atomic lines (N I, O I) corresponds to the low-energy, low-density pre-discharge plasma. Minimal ionization indicates that thermal equilibrium is not achieved, and optical emissions are weak.

(b) Return stroke phase: This is characterized by intense atomic and ionic lines. N II and O II emissions, combined with H-, signify high temperatures and complete dissociation and ionization of atmospheric gases. Stark-broadened lines corroborate high electron density, consistent with a rapidly heated plasma channel [42, 43].

(c) Continuing current phases: As the current decays, the plasma undergoes cooling and recombination. The appearance of CN and OH bands suggest molecular reformation in the partially ionized gas. The dominance of neutral atomic lines over ionic ones supports the observed drop in the relevant parameters.

The correlation is thus as follows:

(a) High $T$, High $n_e \rightarrow$ Dominant ion lines (N II, O II).

(b) Moderate $T$, Recombining plasma $\rightarrow$ Neutral lines (N I, O I), some molecular bands.

(c) Low $T$, Decayed plasma $\rightarrow$ Molecular emissions (CN, OH).

This systematic spectral evolution strongly supports the use of optical emission as a non-intrusive diagnostic of lightning channel plasma.

The outcomes of this study are significant in several spheres of lightning sciences, such as;

(a) Validation of EM field models: Derived plasma parameters can be fed into electromagnetic field solvers for improved accuracy in return stroke modelling.

(b) Remote sensing of lightning severity: Spectroscopic data allow classification of lightning type (e.g., CG+, CG−, IC) and intensity.

(c) Atmospheric chemistry: Detection of NOx and OH band emissions help quantify lightning-induced changes in atmospheric composition.

(d) Design of protective systems: A better understanding of plasma dynamics informs shielding and lightning protection engineering.

With our experience in conducting this study, we can make the following recommendations for future investigations in this line.

(a) AI-based multimodal data fusion: Utilize machine learning to fuse EM field, optical, and acoustic data for real-time diagnostics.

(b) Spaceborne spectroscopy: Deploy high-speed spectral imagers on CubeSats to correlate emissions with mesospheric and stratospheric lightning.

(c) Laboratory validation: Reproduce channel plasma behaviour using high-current arc generators and study EM-optical correlations under controlled conditions.

## 5. CONCLUSIONS

This study offers a comprehensive analysis of the lightning discharge process by correlating electromagnetic (EM) field signatures with time-resolved optical spectra to uncover the evolving plasma nature of the lightning channel. Drawing from fundamental theoretical models and validated by high-speed, multimodal experimental observations, we have shown that the thermodynamic state and ionization properties of lightning plasma are both temporally and causally linked to the discharge phase and current waveform.

The integration of electromagnetic field measurements and spectral diagnostics has enabled us to identify distinct plasma states across the temporal phases of lightning: from weakly ionized molecular-dominant regions in the stepped leader phase, to fully ionized, high-temperature atomic and ionic species during the return stroke and recombining molecular plasma during the continuing current and decay stages. This correlation substantiates the physical hypothesis that both the EM field strength and spectral emissions originate from a common underlying cause, the transient plasma properties of the lightning channel governed by energy deposition, current evolution, and atmospheric composition.

Using spectroscopic diagnostics such as Boltzmann plots, Stark broadening, and Saha equilibrium analysis, we have derived quantitative plasma parameters, including electron temperature, electron density, and degree of ionization, and related them to EM field amplitudes and waveforms. The derived parameters not only align with those previously observed in high-speed lightning discharge experiments but also provide new insights into the plasma kinetics and energy transfer mechanisms.

The development of a tabulated correlation framework between spectral features and plasma characteristics represents one of the key contributions of this work. This matrix serves as a powerful tool for both real-time diagnostics and post-event analysis of lightning discharges, with potential applications in atmospheric modelling, lightning protection design, and satellite-based remote sensing.

One significant implication of our findings lies in the improved understanding of the lightning channel's conductivity and how it varies over time. The correlation of optical emissions with peak EM field strengths validates the use of certain atomic transitions (such as H$\alpha$, N II, and O I) as proxies for current intensity and channel ionization. These results support ongoing efforts to use optical observations from ground-based and satellite-borne instruments to remotely assess the strength and potential damage of lightning events.

Furthermore, our approach highlights the importance of synchronizing multi-modal datasets for advanced lightning diagnostics. The precision achieved through microsecond-level synchronization between EM field sensors and optical spectrometers provides an unprecedented temporal resolution that is critical for capturing the fast-changing nature of the lightning channel plasma.

This research opens new avenues for future investigation. One such direction involves the development of machine learning models trained on synchronized spectral-EM datasets to classify lightning type, intensity, and channel evolution in real time. Another area of potential advancement is the use of spaceborne high-speed hyperspectral imaging systems for global lightning surveillance and atmospheric plasma monitoring. The integration of these methods with ground-based electric field mills and very low frequency (VLF) sensor networks can create a comprehensive lightning diagnostic architecture.

Additionally, our findings have implications for high-voltage engineering and lightning protection. The improved understanding of the lightning channel's time-dependent plasma properties can guide the development of more accurate lightning attachment models and enhance the design of grounding systems, shielding configurations, and predictive maintenance strategies for power systems.

In conclusion, this study demonstrates the value of interdisciplinary methods in atmospheric electricity research. The fusion of EM field theory, plasma physics, and optical spectroscopy provides a robust framework for decoding the physics of the lightning channel. As the frequency and severity of lightning events are projected to increase due to climatic changes, such integrated diagnostic approaches will become indispensable for ensuring public safety, protecting infrastructure, and advancing our fundamental understanding of natural electrical discharges.

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