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The Origin of HF and VHF Radio Emissions from Lightning

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14. ABSTRACT
This project aims to understand the production of high frequency (HF) and very high frequency (VHF) radio emissions by various lightning processes. Lightning can produce a very broad spectrum of electromagnetic radiation, which is an integral part of the earth's electromagnetic environment. Theories currently exist to explain the lightning electromagnetic radiation in the low frequency (30?300 kHz) band and below. The characteristics and physical mechanisms of the HF and VHF emissions from lightning, however, are poorly understood. The project's research effort is focused on characterizing the properties of the HF and VHF emissions from lightning as well as investigating the physical mechanisms of their production through electrical breakdown processes in virgin air such as streamers and electron avalanches. To characterize the HF and VHF radiation, we analyze a rich lightning dataset collected in 2016 and 2017 by using a suite of instruments including a broadband radio interferometer. To understand the production mechanisms of HF and VHF radiation, the radio emissions from streamers and electron avalanches are investigated by performing plasma discharge fluid simulations. Built on the knowledge of the radio emissions from individual streamers
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or electron avalanches, we develop a statistical modeling technique to synthesize the radio emission of a large ensemble of streamers or electron avalanches to explain the lightning data. } This is the final year of the research project supported by AFOSR Grant FA9550?18?1?0358. We are very pleased to report that this project has been successfully completed. We have achieved the two main objectives of the project (1) to characterize the HF and VHF emissions from lightning processes and (2) to understand the physical mechanism responsible for their production. Important contributions have been made on various topics related to the production of the HF and VHF emissions and the project has certainly advanced our understanding of lightning physics and effects.

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Final Performance Report for Grant FA9550-18-1-0358: The Origin of HF and VHF Radio Emissions from Lightning

PI: Ningyu Liu

Abstract

This project aims to understand the production of high frequency (HF) and very high frequency (VHF) radio emissions by various lightning processes. Lightning can produce a very broad spectrum of electromagnetic radiation, which is an integral part of the earth's electromagnetic environment. Theories currently exist to explain the lightning electromagnetic radiation in the low frequency (30-300 kHz) band and below. The characteristics and physical mechanisms of the HF and VHF emissions from lightning, however, are poorly understood. The project's research effort is focused on characterizing the properties of the HF and VHF emissions from lightning as well as investigating the physical mechanisms of their production through electrical breakdown processes in virgin air such as streamers and electron avalanches. To characterize the HF and VHF radiation, we analyze a rich lightning dataset collected in 2016 and 2017 by using a suite of instruments including a broadband radio interferometer. To understand the production mechanisms of HF and VHF radiation, the radio emissions from streamers and electron avalanches are investigated by performing plasma discharge fluid simulations. Built on the knowledge of the radio emissions from individual streamers or electron avalanches, we develop a statistical modeling technique to synthesize the radio emission of a large ensemble of streamers or electron avalanches to explain the lightning data.

This is the final year of the research project supported by AFOSR Grant FA9550-18-1-0358. We are very pleased to report that this project has been successfully completed. We have achieved the two main objectives of the project (1) to characterize the HF and VHF emissions from lightning processes and (2) to understand the physical mechanism responsible for their production. Important contributions have been made on various topics related to the production of the HF and VHF emissions and the project has certainly advanced our understanding of lightning physics and effects.

1 Main Research Activities

The final year of the research work conducted for this project focused on completing the development of a new streamer code that allows for efficient, 3D simulations. We also collaborated with several research groups on the analysis and interpretation of lightning radio data collected by different instruments. The main research activities performed and progress made during this year are summarized below.

- Three papers were published this year, including a publication in prestigious *Science Advances*. Another paper is under review.
- We continued the work to develop a new streamer simulation code based on the adaptive mesh refinement (AMR) technique. A manuscript reporting the implemented method and the developed code was written and submitted for publication in *Journal of Computational Physics* (*Liu*, 2022a,b).
- Working with our collaborators in the Netherlands, we analyzed several unusually slow thunderstorm discharge events observed by the LOFAR radio telescope, which resulted in a publication in *Geophysical Research Letters* (*Sterpka et al.*, 2022).
- We participated in a study to investigate the development of a gigantic jet and associated radio emissions. The paper was published in *Science Advances* (*Boggs et al.*, 2022).
- We worked with researchers from Sandia National Lab, University of Oklahoma, and University of New Mexico to use the Long Wavelength Array to image lightning. A methodology for lightning interferometric imaging using the LWA array has been developed (*Stock et al.*, 2023).

2 Significant Results

Below we highlight our work to (1) develop the efficient streamer simulation code in order to accelerate the research progress of understanding lightning and its high frequency electromagnetic radiation through simulation and modeling, and (2) understand lightning initiation and propagation via VHF interferometric analysis of LOFAR lightning data.

2.1 AMPLIFI Plasma Fluid Simulation Code

AMPLIFI (Adaptive Modeling of PLasma Initiation, Filamentation and Interaction) (*Liu*, 2022a,b) is an open-source, high performance plasma discharge fluid simulation code developed by the PI of this grant to simulate plasma discharge fluids, including the ultimate source of the HF and VHF emissions from lightning – streamers. It is based on the Chombo C++ framework (*Adams et al.*, 2019) developed by Lawrence Berkeley National Laboratory for adaptive solutions of partial differential equations. The main features of AMPLIFI that enable efficient, fully 3D simulation of streamers are as follows:

- Adaptive mesh refinement technique for modeling multiscale processes,
- Time-split integration approach for flexibility in modeling various physical processes,

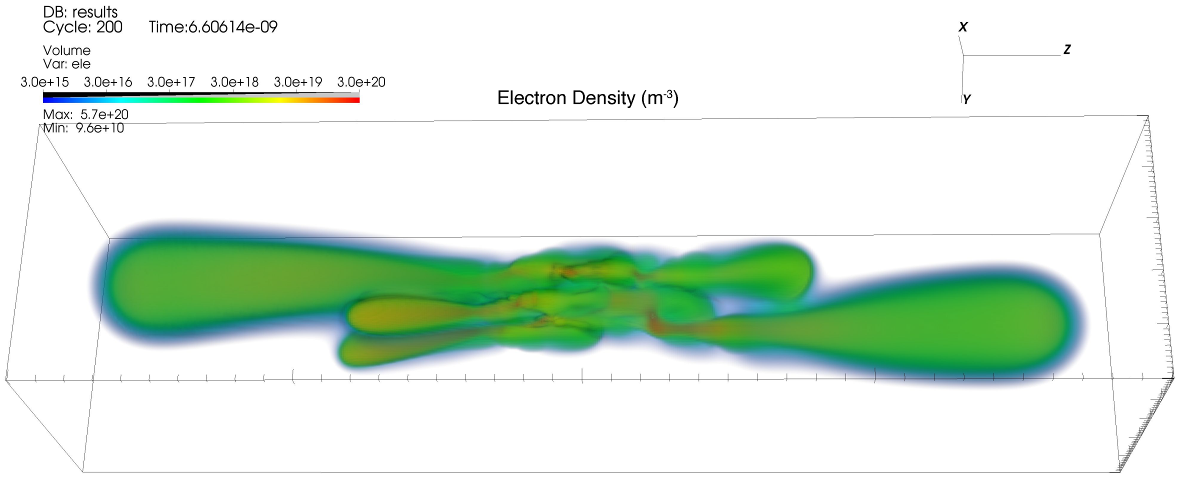

Figure 1: AMPLIFI simulation of a small streamer system in a 3D volume of [0, 1] cm × [0, 1] cm × [0, 4] cm at ground pressure (*Liu*, 2022b). The external electric field has a magnitude of 1.5E_k and points in the -z direction. The left- and right-moving streamer heads are of positive and negative polarity, respectively.

- Proper solvers for hyperbolic, parabolic, and elliptic processes of dielectric breakdown,
- Implicit-explicit time stepping methods to obtain fast and stable solution.

Figure 1 shows an example of what can be simulated with AMPLIFI. A small streamer system with ten double-headed streamers is simulated. The streamers are formed near the center of the simulation domain, with their positive heads propagating towards the left and negative heads towards the right. Very complex plasma structures are formed due to streamer collisions and merging, but there appear to be a dominant left-moving positive head and a dominant right-moving negative head. The simulation was run on a Cray Supercomputer with a requested resource of 64 CPUs of 1.5 GHz and took less than 3 hours to complete. Compared to the streamer code that our group has been using, which led to several publications for this project (e.g., *Shi et al.*, 2019; *Koile et al.*, 2020, 2021), the simulation performance is improved by 2-3 orders of magnitude.

As another example to illustrate the performance and potential applications of this code, Figure 2 shows sprite streamers simulated using AMPLIFI. This simulation was performed to study the ion-neutral coupling through sprite dynamics. In particular, *Liu et al.* (2015) proposed that mesospheric inhomogeneities (neutrals) can play an important role in sprite streamer initiation. The current study was to further investigate the neutral effects on the propagation dynamics of sprite streamers. In the simulation, Gaussian white noise is added to the neutral density to model a perturbed neutral profile at sprite altitudes. The streamer system starts as a single downward streamer from an ionization inhomogeneity placed near the top of the simulation region. As it propagates download, it branches repeatedly, resulting in a dozen of streamer heads at the end of the simulation. The branching is caused by the neutral density perturbations. Additional simulations show that without the neutral perturbations, the streamer formed from the inhomogeneity at the top propagates to the bottom of the simulation region without any branching. These results demonstrate that small scale neutral density perturbations can have strong

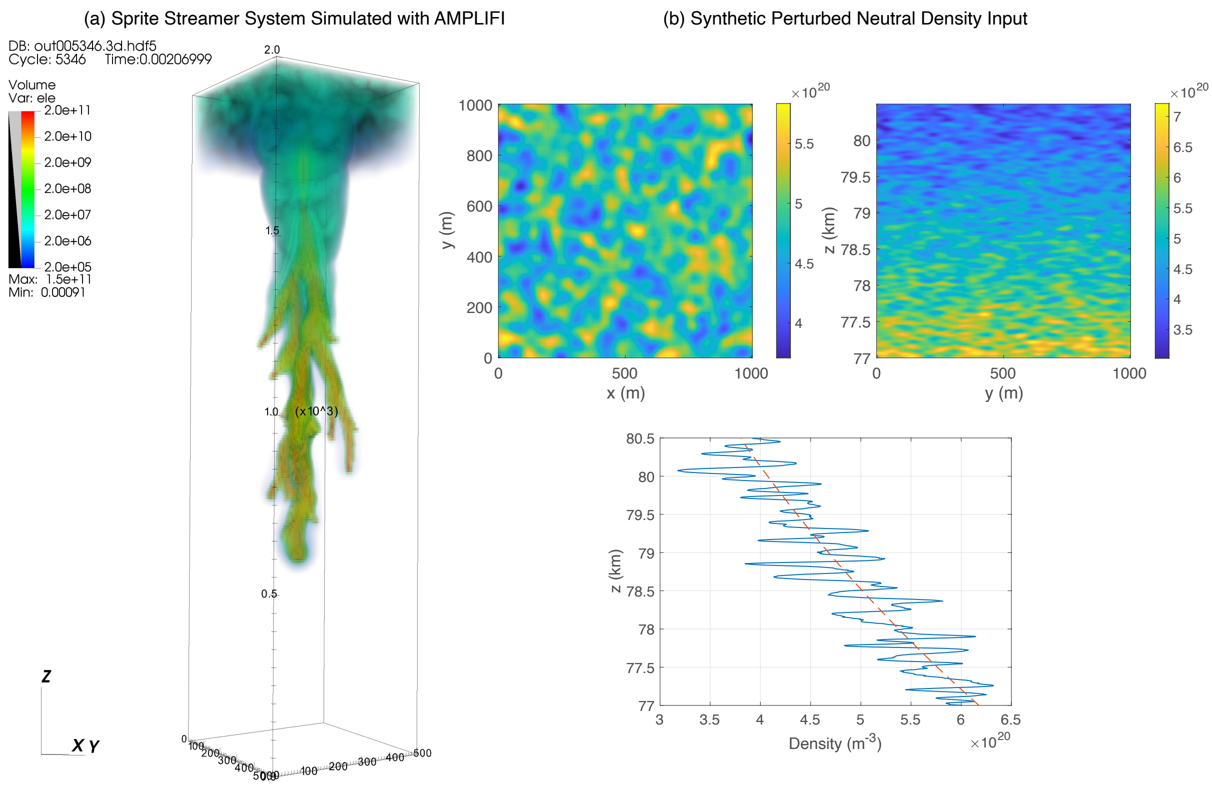

Figure 2: Effects of neutral perturbations on the evolution of sprite streamers. (a) AMPLIFI simulation of sprite streamer dynamics. The tree-like sprite streamer structure results from streamer branching triggered by neutral density perturbations. (b) The perturbed neutral density profile used as the input to the AMPLIFI simulation shown in (a).

impact on the propagation dynamics of streamers. As it is generally difficult to observe these perturbations at sprite altitudes, sprite streamer observations can potentially provide useful information to complement other data. This study was performed in conjunction with the support from the AtmoSense program.

A manuscript (*Liu*, 2022b) that documents the numerical methods implemented in AMPLIFI and its performance is currently under review for publication in *Journal of Computational Physics*. Furthermore, we have also made this code freely available for others to use (*Liu*, 2022a). It is expected that this code will be used by our group for the foreseeable future.

2.2 Ultra-Slow Discharges Preceding Lightning Initiation

Lightning propagation is generally a very fast process, although the speed varies depending on the type of specific lightning discharges. The slowest reported speeds are positive leaders, which are commonly reported in the range of 1.6-3$\times 10^4$ m/s, with an average velocity of about 2$\times 10^4$ m/s. Negative leaders generally propagate at higher speeds with a typical range of 1-6$\times 10^5$ m/s, i.e., about an order of magnitude higher than positive leaders. Working with the LOFAR lightning team in the Netherlands, we found ultra-slowly propagating discharge events with speeds in the range 1-13$\times 10^3$ m/s, an order of magnitude lower than the speed of positive leaders. Furthermore, most slow events appear not to be directly involved with lightning initiation. For one particular event, a lightning leader, however, forms about 40 ms later within 50 m of the discharge, likely within the same high field region. A second slow event forms 9 ms prior to the initiation, and leads into the negative leader. This sheds light into lightning initiation process, as it suggests that the classic streamer cascade model of initiation is not always a definitive process.

Figure 3 shows interferometric imaging results of a slow propagation event and the subsequent initiation of a negative lightning leader, which leads to a flash observed on 27 June 2020 at about 14:51 UTC. The imaging was performed with 183 antenna pairs. As shown by the figure, the sources corresponding to the slow propagation event were found to develop about 65 ms before the initiation of the negative lightning leader and about 50 m southeast from the initiation location. The event took place 19 km west, 12 km north, and at an altitude of about 6 km from the LOFAR core. As the slow propagation moves in the same direction as the negative leader, this indicates that its polarity must also be negative.

We have found additional 10 such slow propagation events in 5 different flashes observed by LOFAR. Most of these events do not lead to lightning initiation, which suggest a new form of lightning initiation and/or failed initiation characterized by velocities orders of magnitude slower than any known discharge process. Given these facts, it is essential that further study address the outstanding questions to find their proper role in both initiation and failed initiation as well as the underlying physics behind their ultra-slow propagation speeds. This study was published in *Geophysical Research Letters* (*Sterpka et al.*, 2022)

3 Personnel

Dr. Ningyu Liu (PI) is responsible for all aspects of the project. He leads the efforts in model development and lightning data analysis. He also supervises the students working on this project.

Dr. Joseph R. Dwyer (co-PI) provides assistance in data interpretation and student supervision.

Chris Sterpka (graduate student) conducts analysis of LOFAR lightning observation to understand lightning processes.

Stephen Horn (graduate student) develops a radio instrument for lightning observation.

Mehran Motamedi Kouchaksaraei (graduate student) provides assistance in developing 3D plasma fluid simulation code.

4 Publications

Liu, N. Y., Adaptive modeling of plasma initiation, filamentation and interaction, Journal of Computational Physics, under review.

Stock, M., J. Tilles, G. B. Taylor, J. Dowell, and N. Y. Liu, Lightning interferometry with the Long Wavelength Array, Remote Sens., 15, 3657, https://doi.org/10.3390/rs15143657, 2023.

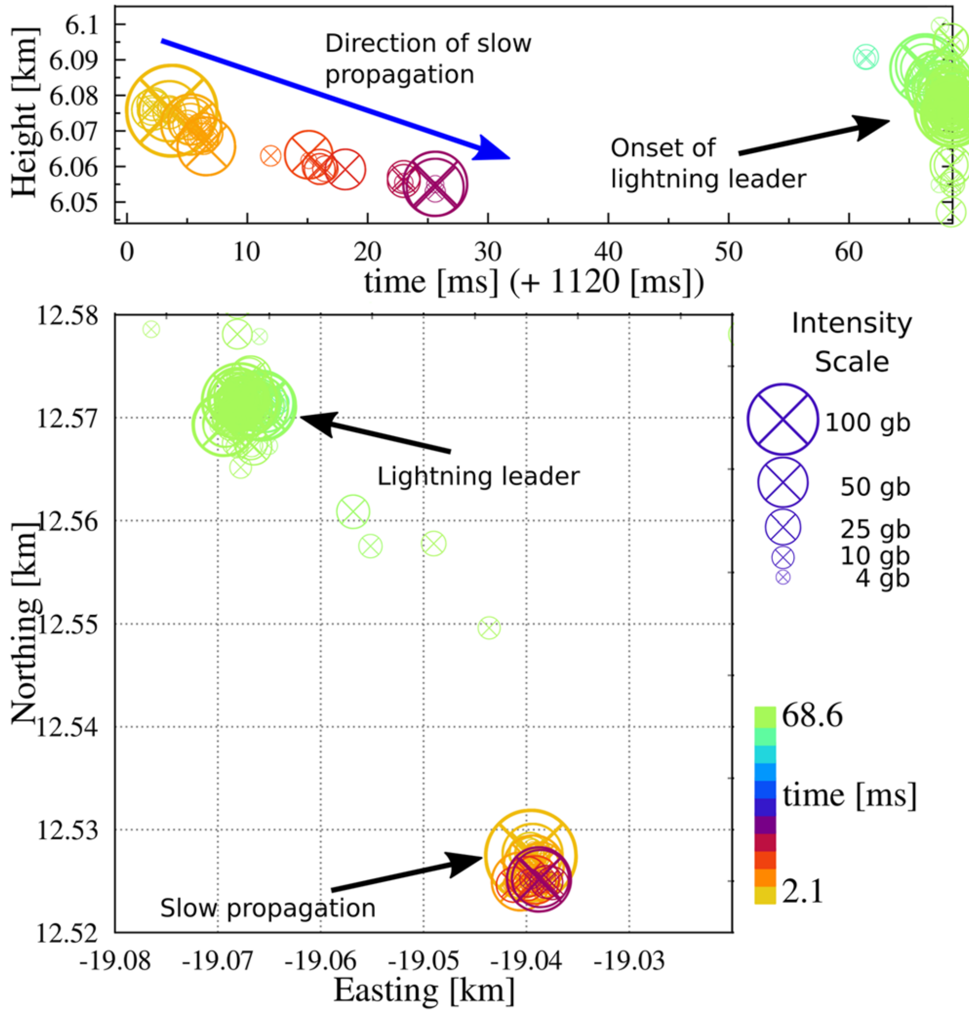

Figure 3: Interferometric imaging of a slow propagation event and the subsequent lightning leader initiation. The flash occurred on 27 June 2020 at about 14:51 UTC. The top panel shows the altitude versus time plot of LOFAR identified VHF emission sources and the bottom panel shows the ground projection of the same sources. Each source is represented by a "wagon wheel", with its center denoting the exact location of the source and its size the intensity of the source. The timing information is also coded in color. The plots show that the development of the slow propagation is followed by the onset of a lightning leader and that the intensity of the slow propagation is similar to the intensity of the first few sources of the lightning leader. Note that overlap of the sources in the ground projection indicates the close proximity of the separate discharges.

Sterpka, C. F., J. R. Dwyer, N. Y. Liu, N. R. Demers, B. Hare, O. Scholten, and S. ter Veen, Ultra-slow discharges that precede lightning initiation, Geophysical Research Letters, e2022GL101597, https://doi.org/10.1029/2022GL101597, 2022.

Boggs, L. D., D. Mach, E. Bruning, N. Y. Liu, O. A. van der Velde, J. Montanya, S. Cummer, K. Pavilec, V. Chmielewski, D. MacGorman, and M. Peterson, Upward propagation of gigantic jets

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5 Presentations

(invited) Liu, N. Y., Radio interferometer for thunderstorm studies (RIFTS), Symposium on Radio Observations of Theory of Atmospheric Discharge Processes, University of Bath, June 26-30, 2023.

Liu, N. Y., Three-dimensional fluid simulation of streamers using AMPLIFI, AGU Fall Meeting, December 12-16, 2022.

Liu, N. Y., Advancing the understanding of lightning and transient luminous events through the study of streamers, Asia Oceania Geosciences Society 19th Annual Meeting, August 1-5, 2022.

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Sterpka, C., J. Dwyer, N. Liu, N. Demers, B. M. Hare, O. Scholten, and S. ter Veen (2022), Ultra-slow discharges that precede lightning initiation, *Geophys. Res. Lett.*, *49*(24), e2022GL101597, doi:10.1029/2022GL101597.

Stock, M., J. Tilles, G. B. Taylor, J. Dowell, and N. Liu (2023), Lightning interferometry with the Long Wavelength Array, *Remote Sens.*, *15*(14), 3657, doi:10.3390/rs15143657.