VHF emitting width and 3D polarization of lightning dart leaders

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Abstract

After the lightning initial stage, lightning flash plasma channels (leaders) can become unstable and exhibit current pulses called dart leaders that propagate back down the lightning channel. These pulses are difficult to understand as they are a type of dielectric breakdown on an already existing plasma channel. In this work we present VHF radio observations (30-80 MHz) of three dart leaders with the LOFAR radio telescope with meter and nanosecond level accuracy. We show that the radio emission comes from a meter-level (or smaller) width core. We also present the first 3D polarization data of dart leaders which shows that, at least sometimes, the VHF currents in dart leaders are parallel to the leader channel. Together, these observations reveal that the primary streamer activity in a dart leader comes from a very thin region and does not significantly involve the corona sheath that was originally established by streamers.

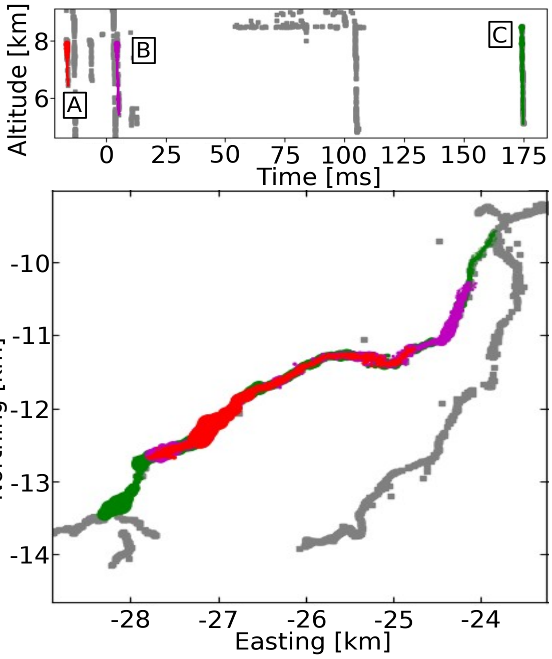

Figure 1: The three dart leaders used in this study: A, B and C. The grey dots are sources located by the impulsive imager, and the colord dots are sources located by the TRI-D beamformer for the dart leaders under consideration in this work. Adapted from [12].

1 Introduction

After lightning initiates, there are negative and positive plasma channels, called leaders, that propagate through the thundercloud seeking regions of opposite charge. As they grow, they develop two primary regions: a hot conducting core that is cm in diameter, and a relatively cool poorly conducting corona sheath that is thought to be at least 10 m in radius [1].

As the lightning channels cool down they somehow become unstable and exhibit strong current pulses, called dart leaders, that propagate in the negative direction back down the previously established lightning channel with a speed around 10^7 m/s [1]. However, it is known that dart leaders cannot be described by transmission line physics (as opposed to return strokes), since their propagation velocity is too low [2], and that streamer phenomena/ dielectric breakdown is central to dart leader propagation due to the fact they emit significant VHF radiation [3,4]. Thus, the propagation physics of these dart leaders is very poorly understood from a theoretical perspective because it is hard to understand how dielectric breakdown can occur on an already established channel, and difficult to observe with high resolution because dart leaders are very fast and the important physics occurs at small scale (meters).

In this work we use the LOFAR radio telescope [5] to observe three dart leaders with the meter and nanosecond scale accuracy needed to be sensitive to the propagation physics of dart leaders. We will show that the VHF emitted by three dart leaders comes from a small meter-level (or smaller) width core and not from the corona sheath. In addition, we present the first measurements of 3D polarization of dart leader VHF emission which shows that (at least sometimes) the VHF emission has polarization parallel to the leader channel. Together, these observations imply that the significant streamer activity occurs close to the conducting core and not in the larger corona region. This is in contrast to a previous work, which observed 2D polarization from dart leaders and showed it was perpendicular to the plasma channel [6].

2 LOFAR Telescope and Imaging Techniques

In this work we use data collected by the 36 Dutch LOFAR radio telescope stations. From each station we use data from 6 LBA (low band antennas), which operate in the 30-80 MHz regime. LOFAR continuously buffers antenna voltages on to a circular antenna buffer, and when a lightning flash is detected this buffer is frozen and 2 seconds of data around the lightning flash are read to disk. [5].

After recording, we pass our data through an analysis chain [7,8,9]. The primary stages consist of RFI cleaning and a timing calibration. After these steps we image our data to find the location of the lightning VHF radio sources using two different techniques. The first technique we call the impulsive imager, which measures time differences using cross-correlations. The impulsive imager is capable of mapping entire lightning flashes which high accuracy and low computational complexity [10].

The primary imaging technique used in this work, however, is our TRI-D 3D interferometric imager [9]. It functions by rasterizing a small (roughly 100 m per side) 3D grid and calculating $\vec{P}(\vec{x},t)$, the dipole moment at each grid location, by summing the measured electric fields according to eq. 1.

$$A\vec{P}(\vec{x},t)=\sum_a \vec{E}_a(t)\, w_a/R_a \qquad (1)$$

Where the sum is over all antennas with index a. $\vec{E}_a(t)$ is the electric field measured by antenna a, with the antenna function and geometric time delays removed. w_a is the weight for antenna a, and R_a is the distance from antenna a to the imaged source location $\vec{x}$. Finally, A is an invertible 3x3 matrix dependent on the arrangement of LOFAR antennas. [9]

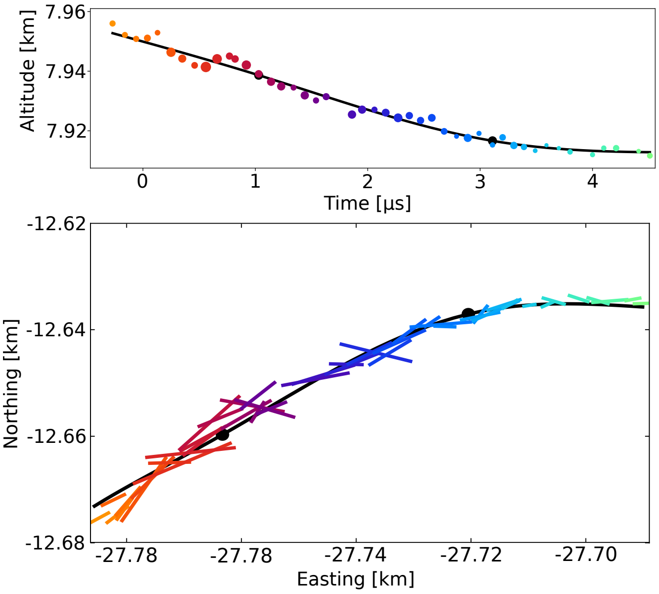

Figure 2: zoom-in to dart C. Lines, colored by time, show the location and direction of source diples; length is proportional to total source intensity Black line shows the spline fit. Two black dots show the spline knot locations.

After imaging every voxel in the box, we chop the time into 100 ns intervals, integrate $\vec{P}(\vec{x},t)$ to find the total intensity in that 100 ns interval per voxel. We then pick the voxel with highest intensity as the source location and intensity in that 100 ns bin. Thus, resulting in one source location every 100 ns. We can also reconstruct the average 3D linear polarization of the radio source by following the techniques laid out in [11].

Since TRI-D can only image small boxes due to memory usage, many boxes were placed along the path of the dart leader in order to image the entire channel. Finally, after imaging we constructed a quadratic smoothing spline through each dart leader, with 20 sources per knot and excluded (only from the spline fit) sources more than 10 m from the spline.

3 Results

In this work we present three subsequent dart leaders, named A, B, and C, that we imaged with our TRI-D imager. These three dart leaders occurred during a flash that was observed at 21:03:06 UTC on 24th of April 2019, and were also investigated in [12]. Figure 1 shows the dart leaders A, B and C, as well as other radio sources in grey that are on different lightning channels.

Figure 2 shows a zoom-in to a small section of dart leader C. This figure shows the location and direction of the source dipole moments, the smoothing spline fit, and the knot locations. This figure demonstrates the two main points of this work, firstly that the sources have a very small scatter; they lie within a few meters of the spline.

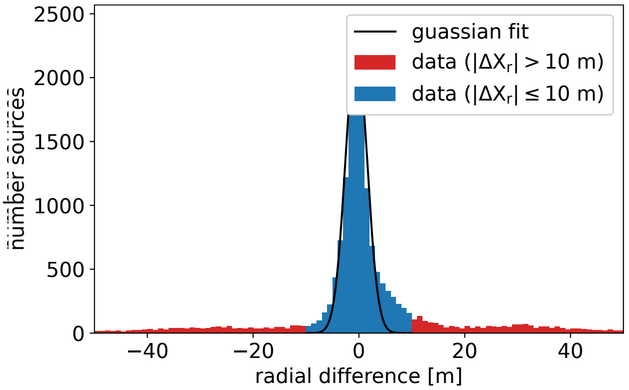

Figure 3: histogram of difference between source and spline locations, along the radial direction from the LOFAR core. Blue bins are those where the sources are within 10 m of the spline, and are used to fit a gaussian function which is shown as a black line. The gauassian has a fitted standard deviation of 2.03 m. Adapted from [12].

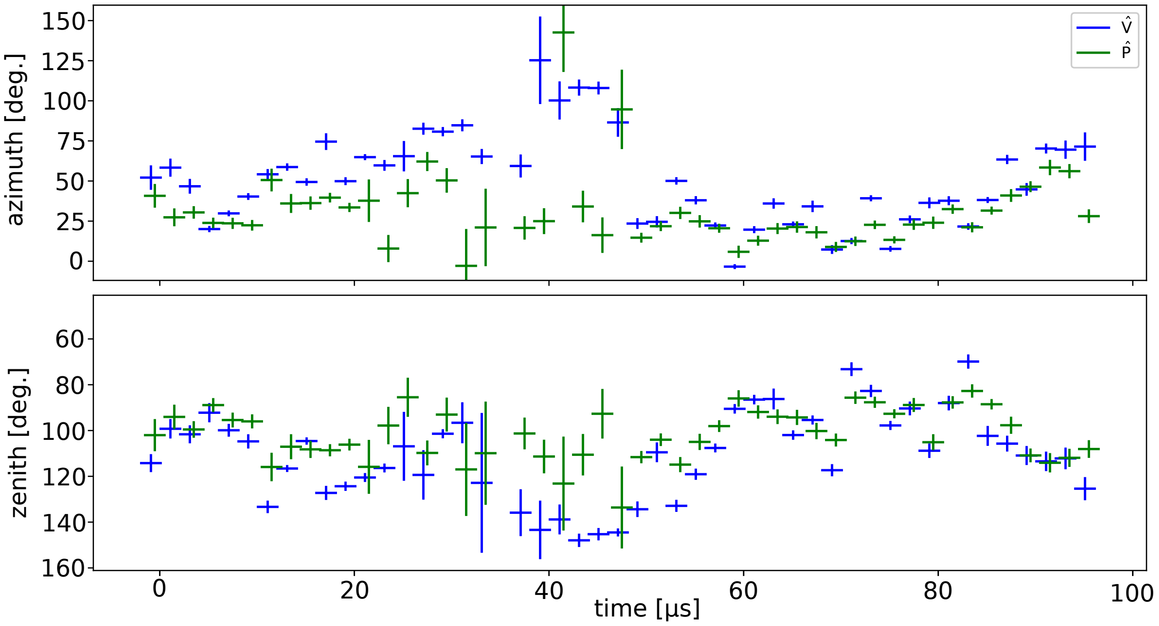

Figure 4: Azimuthal and zenithal angles of the velocity and linear polarization. Blue is the velocity, green is linear polarization. Figure 3 occurs at t=55-59 µs in this plot.

Second, that the polarization follows the leader propagation direction. This can be seen by the fact that the colored lines (the dipole orientations), are roughly parallel to the spline even as the leader path bends.

Figure 3 explores the imaged VHF scatter around all three imaged dart leaders. It shows a histogram of the difference between the source locations and the spline locations along the radial direction from LOFAR's core, which is our worst resolved coordinate. Figure 3 shows that our source scatter has two main components, a tight cluster of normally-distributed sources around the spline and a very broad distribution of poorly located sources. The poorly located sources are typically due to multiple lightning radio pulses interfering with each other and thus confusing the imager. In order to find the width of the central guassian, we fitted the histogram bins (only using the ones where the radial difference was less than 10 m) with a gaussian. With this procedure we find that standard deviation is 2.03 m, which is exactly what we would expect based on source location error, and on the spline not perfectly fitting the lightning channel. Therefore, figure 3 shows that the imaged width of these three dart leaders is due to noise and analysis artifacts and the VHF width of these three dart leaders must be thinner than 2 m.

Finally, figure 4 shows polarization and velocity data from a 100 µs duration section, which includes the data shown in figure 2. In figure 4 we binned the dipole sources into 2 µs width bins. For every bin we found the average velocity (simply by fitting a line to the source locations), and we found the direction of the average polarization using principle component analysis.

Figure 4 demonstrates that, at least for this section of dart leader, the linear polarization roughly follows the direction of propagation of the leader. Primarily, time 0 to 20 µs, and 60 to 80 µs show similar variations in both polarization and velocity. Data between 20 to 60 µs, however, shows significant scatter in the polarization. It should be noted that we did select this section of dart leader on the basis of how clearly the polarization follows velocity, and that different dart leader sections can vary. Some sections look like the 60-80 µs in figure 4, others are more scattered like 20-60 µs. The reason for the large scatter in the polarization is still not clear; i.e. if it is due to imaging artifacts or has a physical origin. However, Figures 2 and 4 do demonstrate that at least some sections of dart leaders have a linear VHF polarization parallel to the direction of leader propagation.

4 Discussion and Conclusion

In this work we have shown that VHF emitting width of dart leaders is very small, around a meter or smaller, and that the linear polarization for at least some dart leaders is parallel to the leader channel. These results have significant physical implications. We know that the VHF emission from lightning comes from streamers [3,4]. This strongly implies that the primary streamer activity during dart leader propagation occurs primarily around or inside the hot conducting channel, and not in the 10 m wide corona sheath the was established by streamers during the previous leader. Streamers can propagate without emitting significant VHF (as evidenced by the fact positive leaders are often invisible in VHF [13]). So there could be VHF invisible streamers in the corona sheath, but they must be much weaker or more smoothly propagating than the streamers near the leader core that are producing the VHF.

[6] measured the 2D polarization of VHF emission from a dart leader, and found it was not parallel to the channel. It is possible that different dart leaders have different

propagation properties (e.g. we know they come in stepped and non-stepped varieties [1]), and thus possibly have different polarization properties. This only goes to show that there is significant work to be done in the science of lightning radio polarization, which is now coming of age and promises to give deep insight into lightning propagation physics.

Acknowledgments

The LOFAR cosmic-ray key science project acknowledges funding from an Advanced Grant of the European Research Council (FP/2007-2013) / ERC Grant Agreement n.227610. The project has also received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 640130). BMH is supported by NWO (VI.VENI.192.071) and ERC Grant agreement No. 101041097. LOFAR, the Low Frequency Array designed and constructed by ASTRON, has facilities in several countries, that are owned by various parties (each with their own funding sources), and that are collectively operated by the International LOFAR Telescope foundation under a joint scientific policy.

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