URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

New Negative Leader Modes Observed By LOFAR

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Recent work with the LOFAR radio telescope has revealed at least three different types of negative leader modes that we refer to as: "normal" lower altitude negative leaders, rapid negative leaders, and higher altitude negative leaders. LOFAR's 3D meter-scale and nanosecond resolution has revealed that the coronal structure of these three different modes are distinct and not merely spatially-and-temporally scaled versions of each other.

The lower altitude negative leaders occur below 6 km altitude, propagate at about 10^5 m/s, and are generally observed when the leaders are propagating through a lower-altitude charge region or down to ground. They emit bursts of VHF pulses, where the width of each pulse is consistent with the LOFAR antenna response function. Each burst is about 1-3 μs long and are point-like; that is, each burst is consistent with most pulses being emitted around 1 meter of each other. The amplitude of the radio pulses is roughly constant with source altitude. These RF bursts occur roughly 5 m and 10 μs apart.

Around 7 km altitude the negative leaders transition into a higher-altitude mode. This transition does not occur smoothly, as one would expect as a linear response to pressure, but over a very short altitude range (≈ 1 km range). These higher altitude leaders are an order-of-magnitude wider than their lower-altitude counterparts (≈ 100 m, vs 10 m), though it is not clear if this width is due to branching or is an inherent leader width. In addition, higher-altitude leader steps are also much longer (> 100 m, vs 10 m), and the VHF pulses from each step are not point-like, but show bursts that elongate and develop into filamentary structures. The nature of these filamentary structures is not clear, but it is possible they either are long streamers or leader branches. Higher-altitude and lower-altitude negative leaders seem to propagate at similar speeds around 10^5 m/s

Additionally, we observe rapid negative leaders which propagate an order-of-magnitude faster, around 10^6 m/s. They emit significantly more radio energy across a very wide band from 1 MHz up to 100 MHz than the other two types of observed leaders. Rapid negative leaders are typically observed during the initial-stage of lightning development, when their radio bursts are observed as initial breakdown pulses. However, they quickly develop multiple branches so that the individual bursts are not easily distinguished. Each radio burst occurs simultaneously with large (100 m) forward steps. Rapid negative leaders, however, can also develop during later portions of the lightning flash, as we have observed them transition both to-and-from more "normal" lower altitude negative leaders. We believe negative leaders transition into this rapid mode when there is a particularly large electric field.

We will discuss and compare these three leader types. The immediate conclusion from our work is that there is not only one "kind" of negative leader. There are multiple negative leader modes, and the chaotic nature of lightning leader plasma physics results in near phase-change like transitions between these different modes. In addition, LOFAR is sensitive to fundamental corona physics, and future work should be able to extract even finer detail that should help guide leader modeling to understanding how these different modes propagate. There is significant work that can still be done to understand negative leaders and how their properties vary with electric field and pressure, and it is very possible that we will discover even more negative leader modes in addition to these three.