Investigating Lightning Initiation using Radio Interferometry

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Abstract

Lightning is a hot (~30,000 K), highly-ionized plasma channel extending many kilometers in length, lasting from tens of milliseconds up to a few seconds long, and carrying extremely large electric currents (up to hundreds of kiloamperes) through the turbulent, extremely cold and wet interiors of thunderclouds, as well as outside of clouds. Ever thought of how lightning gets started? We know that lightning does not start out as a hot, highly-conductive channel, or a leader, but starts out as a cool, lower-current discharge process called a streamer, which has a similar appearance as the luminous filament seen in a plasma globe. However, mysteries still abound. Lightning typically originates deep within thunderclouds, making observations difficult, and observing initiation is altogether impossible with optical instruments. Radio-sensing instruments, on the other hand, allow researchers to detect the electrical activity within thunderclouds, allowing observations of lightning's first moments. Here we present radiofrequency (20-80 MHz), sub-microsecond interferometric observations of the initial processes preceding leader formation that occur during the first few milliseconds of a lightning flash. Based on the observations, we investigate when the hot leader channel forms.

Broadband radio interferometry. One way to investigate the fast in-cloud processes associated with lightning inititiation and propagation is to use a broadband radio interferometer. The interferometer consists of three 20-80 MHz dE/dt antennas oriented in an equilateral triangle configuration, with 100-meter baselines and 16-bit resolution. The interferometer locates lightning VHF sources in two dimensions (azimuth angle and elevation angle), and we can map the source locations over time to reveal the spatio-temporal dynamics of the discharge. A synchronously-digitized "fast" antenna (FA) measures the accompanying 100 kHz-1MHz waveform in the center of the array.

Background

What is lightning? When we talk about lightning, we mean that a lightning leader has formed. Lightning leaders are hot, very conductive, highly ionized plasma filaments [Walker and Christian, 2014], and are optically bright. Lightning leaders are what people see with the naked eye when a lightning flash touches ground. Sometimes lightning leaders can be seen along the bottoms of clouds, and they are what makes a cloud light up fantastically during in-cloud lightning. Streamers, on the other hand, are not as conductive, and are optically dim in comparison. Streamers are a precursor to leader formation, and are what actually "lead" the leader, as shown by the lab-based observations in Figure 1. Similar structures are seen in natural lightning (Figure 2). A large streamer system can funnel the relatively small amount of current from each streamer into a common point, such that the currents add at that point and can heat the air substantially to form the leader.

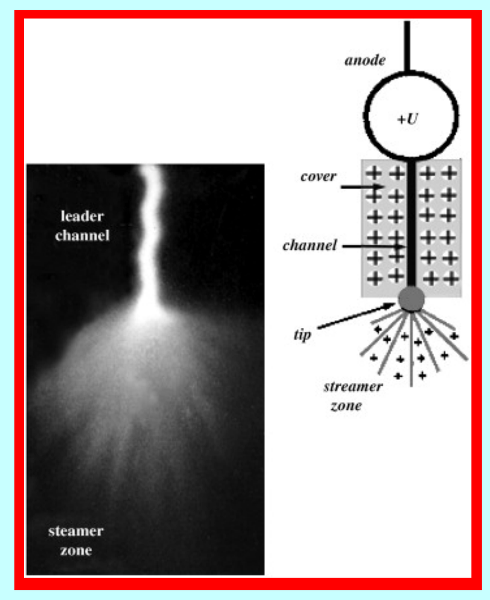

Figure 1. Laboratory leader discharge. Adapter from Raizer et al. (2007) [doi:10.1016/j.jastp.2007.02.007]

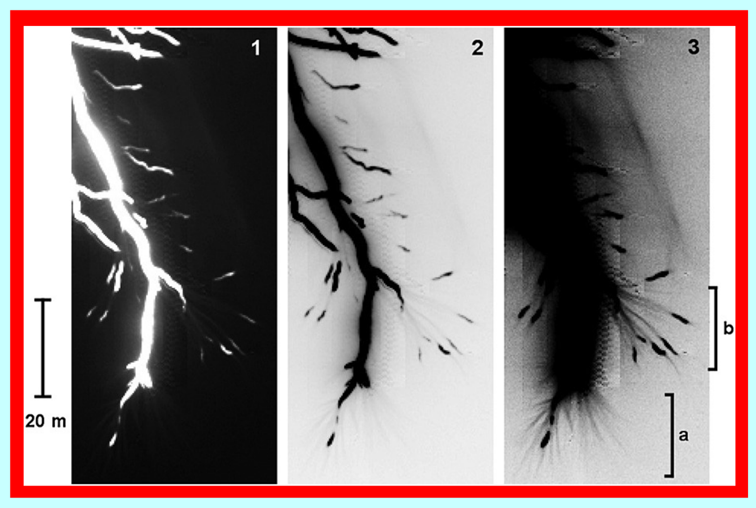

Figure 2. High-speed (99-microsecond exposure) photograph of lightning leader tip (bright feature in panel 1), streamer zone (bracket a in panel 3), and space leaders (bracket b in panel 3). Adapter from Petersen and Beasley (2013) [doi:10.1002/2013JD019910].

Lightning propagation Once the leader is formed, things get really wierd. The photograph in Figure 2 shows that a space leader can form out in front of the main negative leader channel, and then travels back toward the main channel, connecting to it, and hence the whole channel effectively moves forward. That is, it appears to be more energetically favourable for a positive leader to form and move back toward the main channel, than for the the negative-polarity channel to propagate forward smoothly. This process as a whole is called a stepped leader, but negative leaders don't always step!

Lightning initiation. In a lab setting, streamers and leaders are initiated at an electrode where the electric field exceeds the threshold for dielectric breakdown in air. However, deep inside a thundercloud, which is masked by cloud, water, and ice, it is unclear what sort of electrode gets lightning started. To further complicate matters, in-cloud measurements of thunderstorm electric fields have consistently been below the threshold for dielectric breakdown in air [Stolzenburg et al., 2007, doi:10.1029/2006GL028777]. This suggests that thundercloud electric field enhancements take place locally, probably enhanced in the vicinity of cloud particles, probably ice crystals in particular. Positive streamers would occur before negative streamers, given that they require a lower potential to initiate. Positive streamers initiating on ice hydrometeors has proved to be a possible mechanism via numerical simulations, as demonstrated in Figure 3. However, proving that this is happening during real lightning initiation is very difficult. Moreover, it is unclear when the transition from streamer to leader occurs.

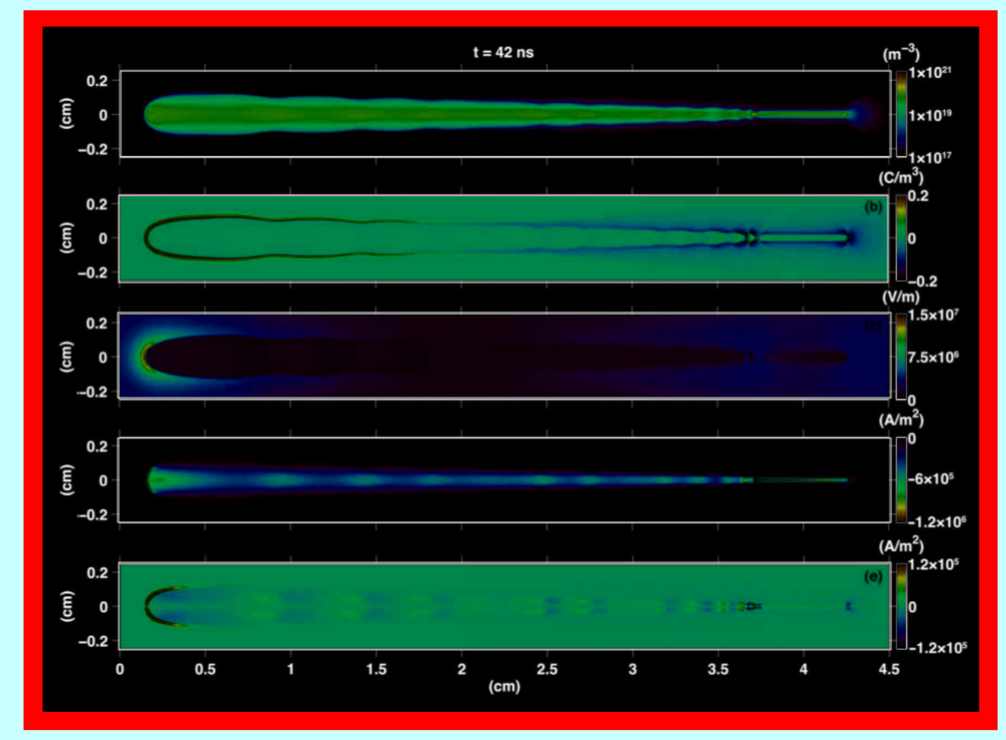

Figure 3. Simulated positive streamer initiated from hydrometeor. Adapted from Shi et al. (2016) [doi:10.1002/2015JD024580].

Results

Figure 4 shows the interferometer-located sources of a hybrid flash in azimuth and elevation angle, as well as elevation versus time. The sources are coloured by received VHF power on a relative scale. The negative leader consists mostly of the brighter (pinkish) sources that come to ground (near 0 degrees elevation angle), while the positive leader can be seen as the mainly dark-blue sources, moving laterally between about 10 and 20 degrees elevation angle. The VHF (gray) and FA (black) waveforms are also shown for the duration of the flash.

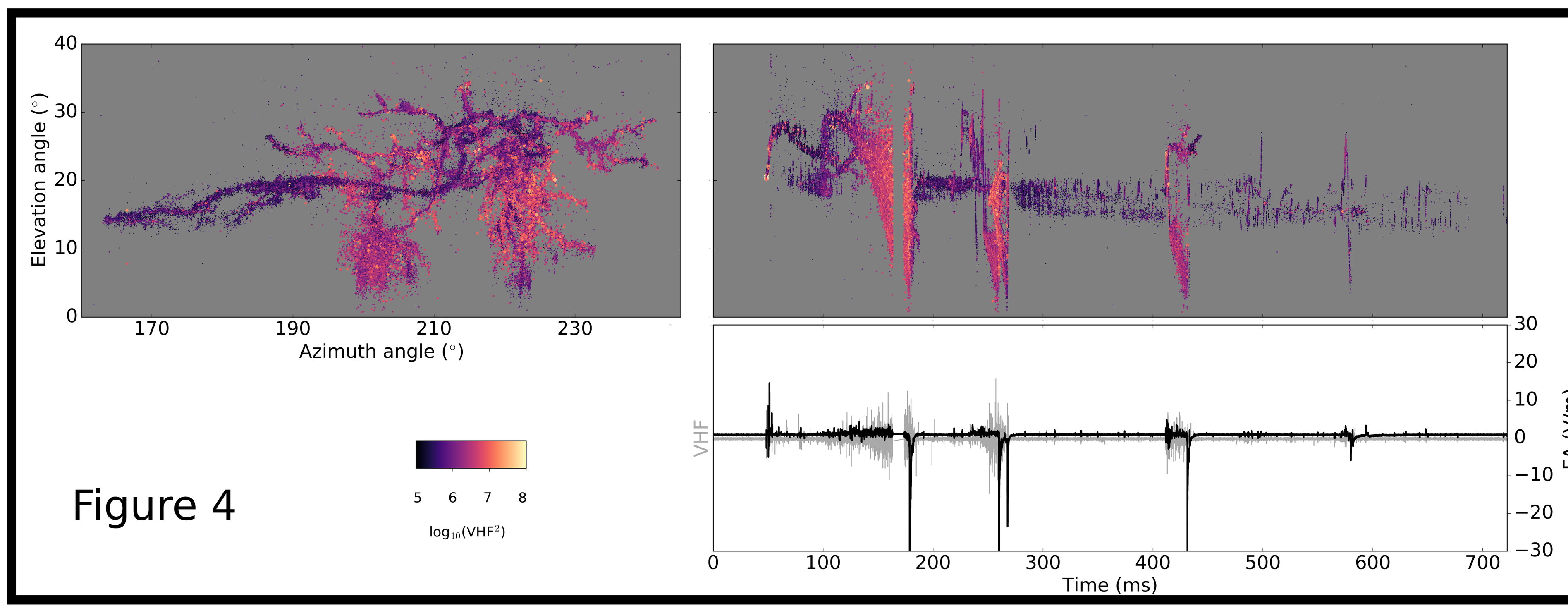

Figure 4

Though the hybdrid flash lasts for almost 1 second, we are mostly interested in just the first few milliseconds of the flash. Figure 5 shows the first 7 ms of the flash, during which the initiating event occurs (near 48.4 ms), and a series of pulses in the VHF and FA signals occur as the discharge proceeds higher in elevation. The initiating event is called a narrow bipolar event (NBE) and the pulses are called initial breakdown pulses (IBPs). Most lightning flashes seem to have these features, though there are exceptions.

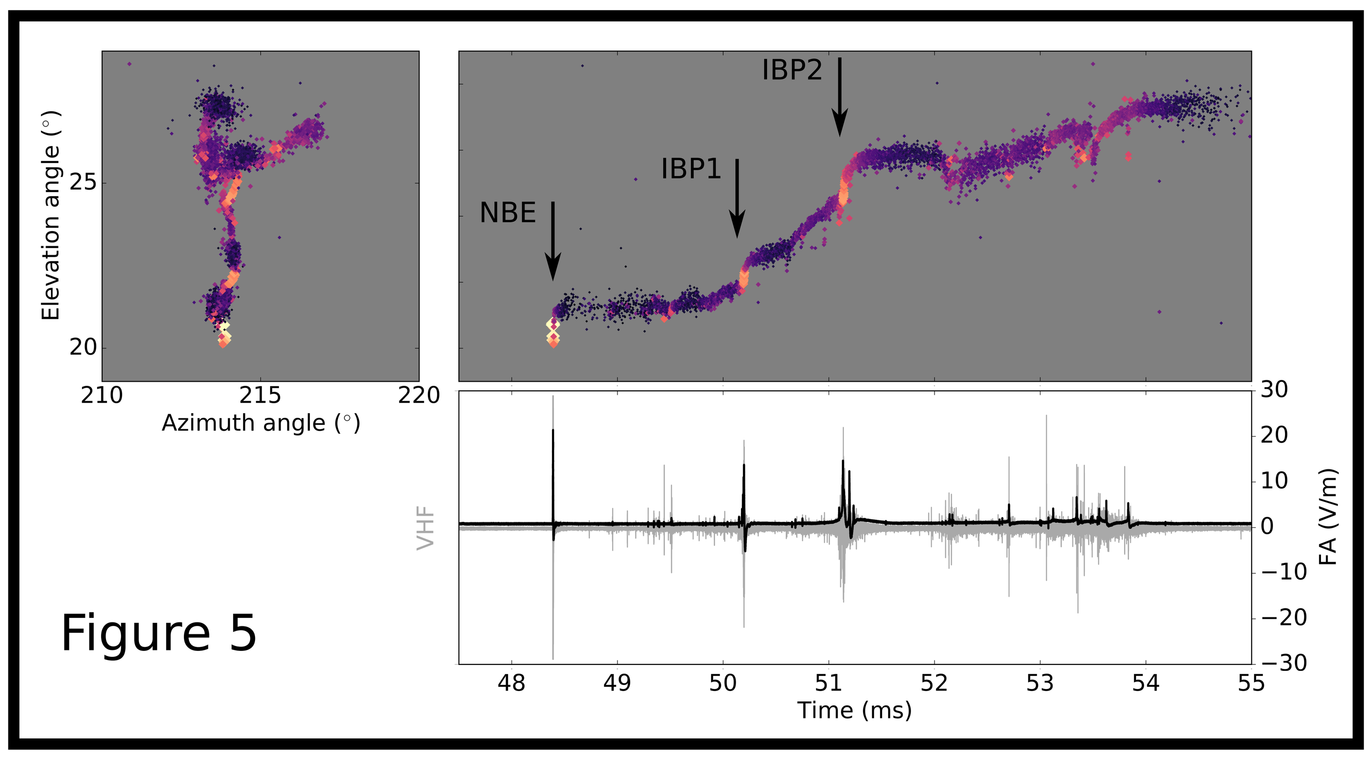

Figure 5

Figures 6, 7, and 8 show detailed observations of the flash-initiating NBE, and IBPs 1 and 2, respectively, along with spectrograms of their VHF and FA signals. Activity prior to each event is coloured in black. All three events exhibit fast ($\sim 10^7$ m/s) breakdown, though a clear difference between the NBE and IBPs is the concurrence of the VHF and FA signals. Within the 5.5 ns resolution of the instruments, the NBE VHF and FA signal turn on simultaneously, consistent with other NBE observations. In constrast, for the IBPs, the FA signal can precede the VHF signal by about 0.5-1.0 microsecond, as shown for IBP2.

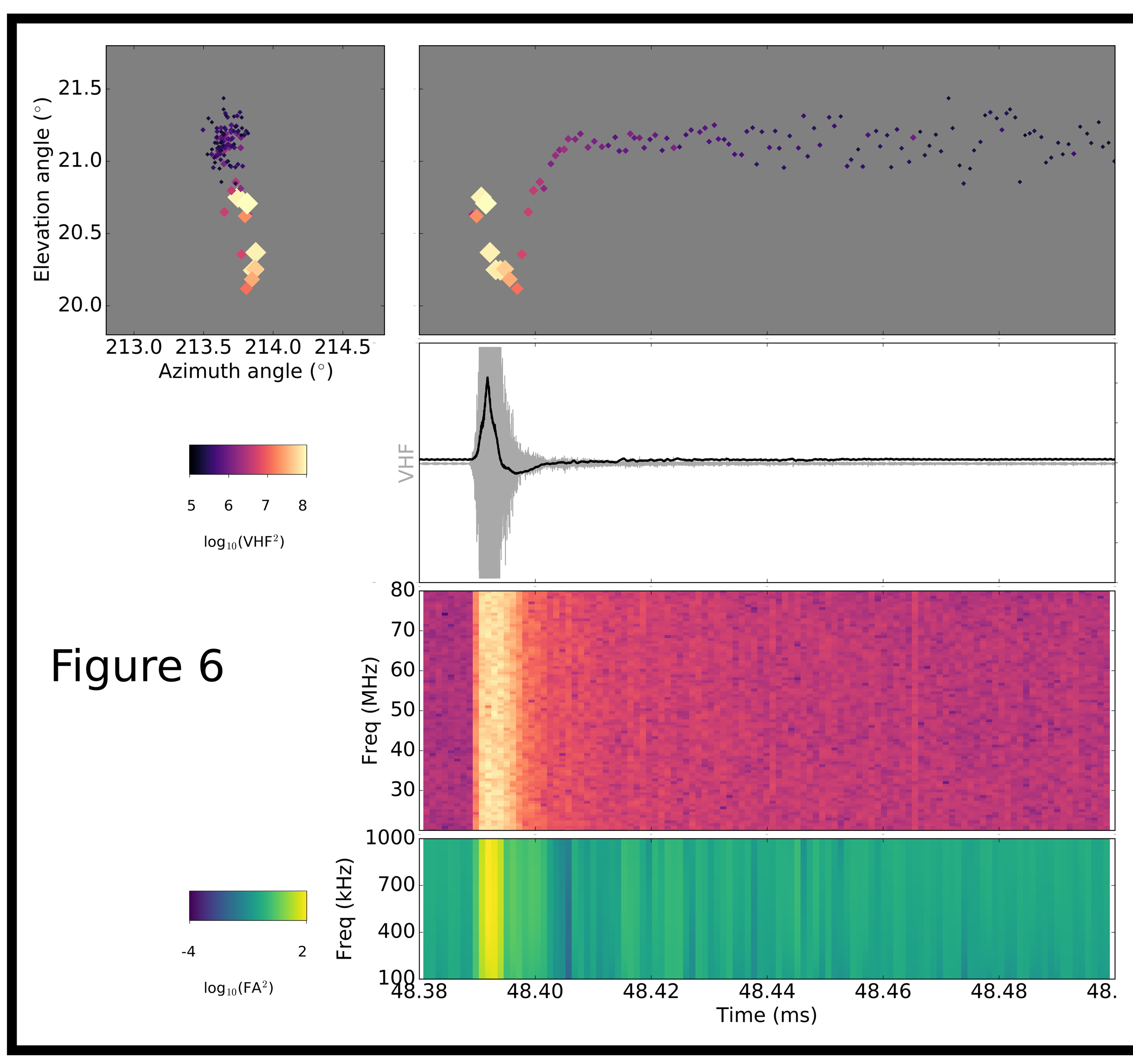

Figure 6

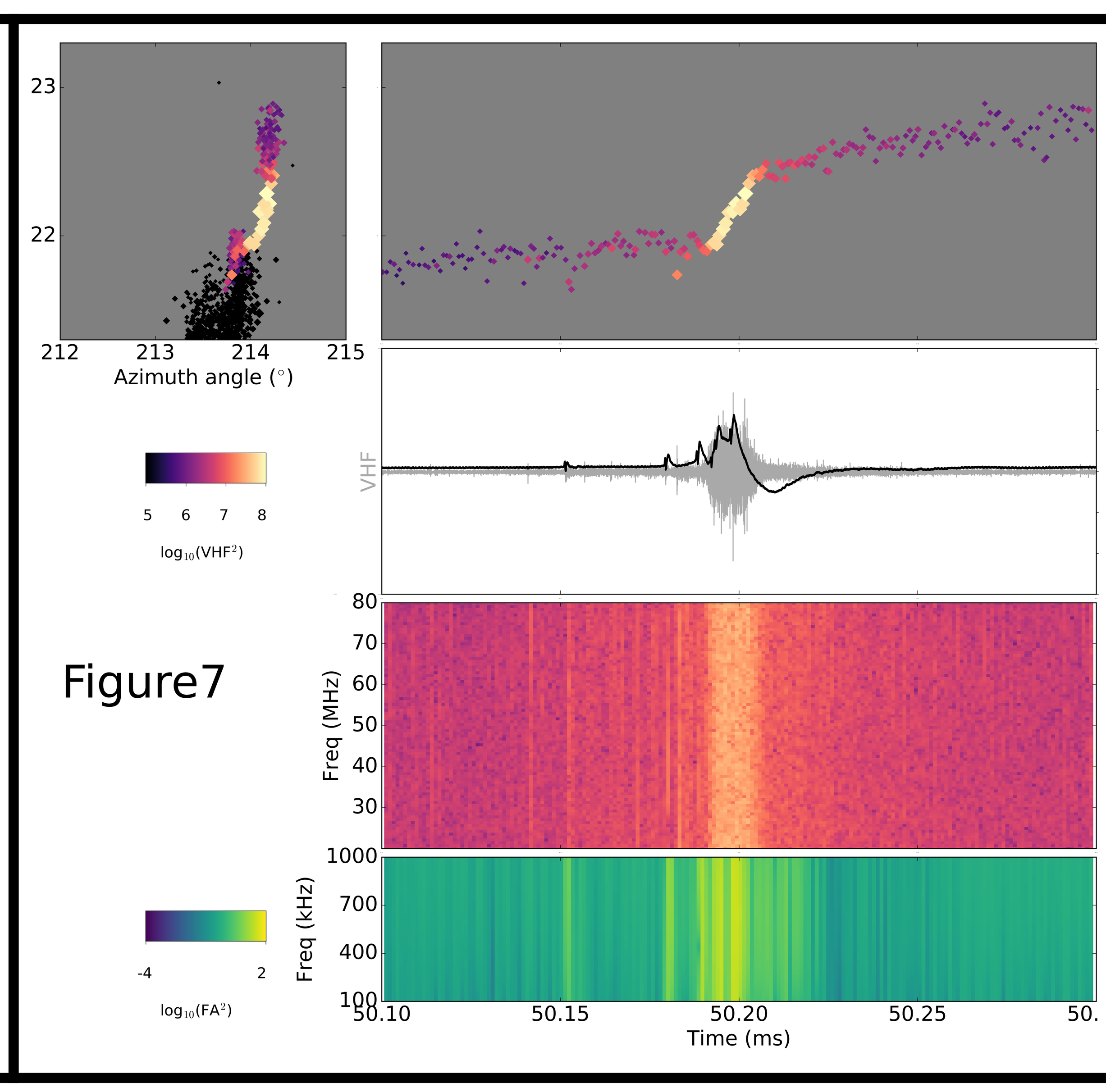

Figure7

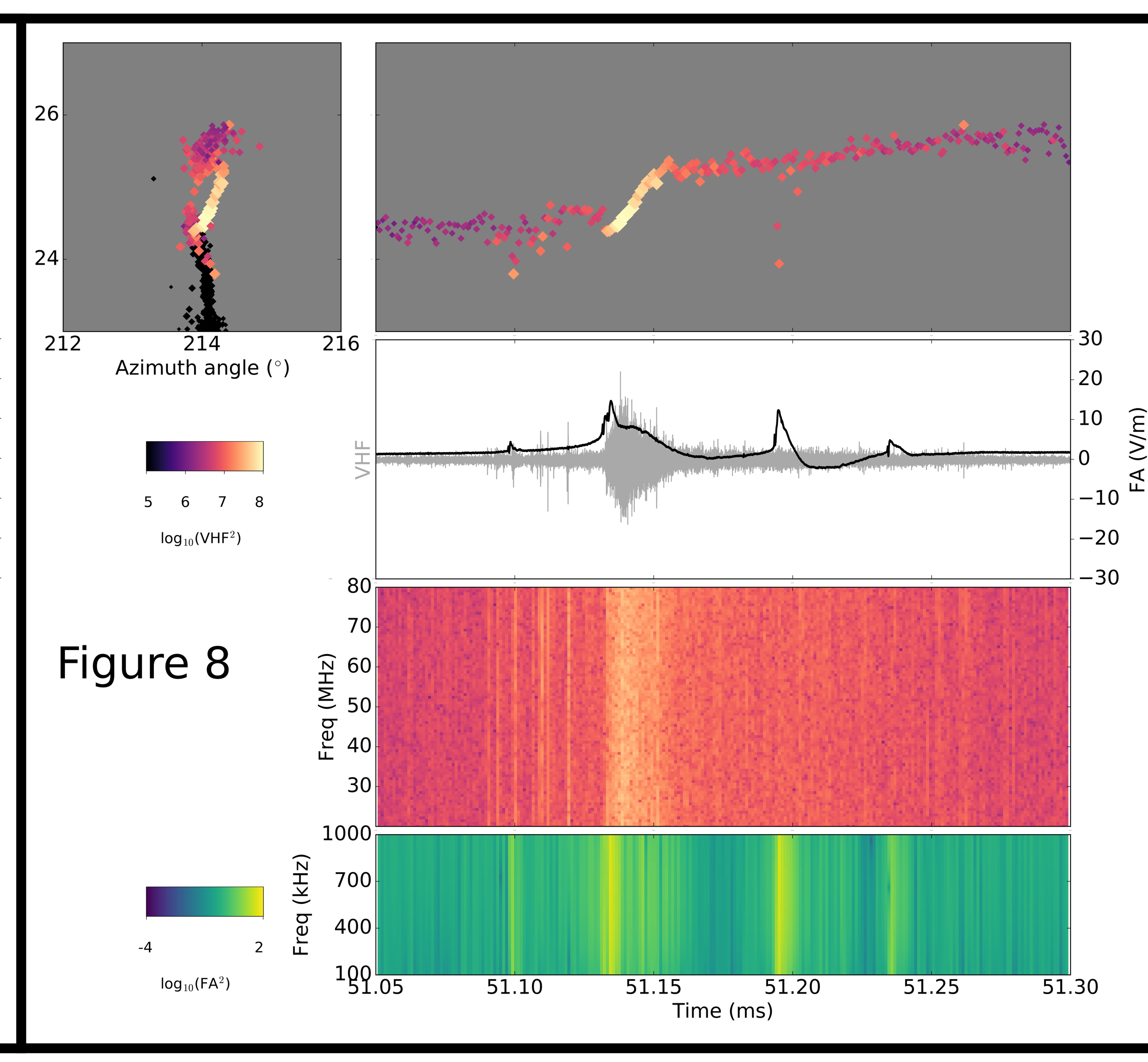

Figure 8

Conclusions

NBEs are considered a streamer process, given the fast speed of the breakdown propagation, and the simultaneity of the VHF and FA signals. IBPs also exhibit fast breakdown, but the time lag of the VHF with respect to the FA signal suggests that streamers (manifested in VHF signal) may not be producing all of the observed electric current (manifested in the FA signal). Runaway electrons could be playing a role. Moreover, it is not clear if a leader is being formed during an IBP. Especially in IBP2, it seems clear that no leader forms, or else the subsequent breakdown (near 51.20 ms) would not go back down along the already traversed path. Investigating the spectra of IBPs more quantitatively and comparing to the spectra of NBEs could help determine when the leader forms.

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