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Key Points:
- High-voltage laboratory simulation of electrodeless discharge from a hydrometeor array
- A bipolar leader develops from the array of particles in high ambient E field
- The size of the array affects the duration and current of the discharge

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Simulating electrodeless discharge from a hydrometeor array

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Abstract The objective of this research was to test, by means of an experiment in a high-voltage laboratory, the effect of an array of hydrometeors on the processes involved in the streamer-leader formation of lightning. Because the common types of hydrometeors present whenever lightning initiation in thunderstorms occurs are ice particles (graupel, hail, or ice crystals), we used, in this experiment, conductive particles similar to hail in size, with various spacing between them, but all under normal atmospheric pressure and room temperature. The laboratory array was suspended on dielectric threads in a uniform electric field of 1 MV m^{-1} in the middle of the gap between the high-voltage and ground electrodes. During the first phase of the experiment, we studied the formation of a bidirectional arc discharge from the array and the effects of the array's size on the electrical characteristics and on the speed of development of the discharge. We continued with the same objectives in the second phase of the experiment, adding high-speed video observations with a recording speed of 10 Mfps, to observe all stages of the streamer-leader formation.

1. Introduction

The fundamental question of the physics of lightning initiation still remains unanswered, despite the tremendous progress achieved in lightning research in recent years. There are only two rather vague hypotheses that attempt to explain lightning initiation in thunderstorms: The first hypothesis considers hydrometeors as potential nuclei, from which a lightning leader emerges in the region of a high electric field (the "hydrometeor theory"); this hypothesis, however, does not specify a mechanism of the leader initiation process. Laboratory experiments in attempts to confirm this hypothesis have been limited to investigations of corona formation on hydrometeors of different types and in conditions resembling those inside the cloud that were reproduced in small environmental chambers [e.g., *Griffiths and Latham*, 1974; *Coquillat et al.*, 1995; *Petersen et al.*, 2014]. The second hypothesis suggests that cosmic rays initiate a relativistic runaway electron avalanche (RREA) breakdown [*Gurevich et al.*, 1992; *Roussel-Dupre et al.*, 1993] that leads to the initiation of a lightning leader. This hypothesis was put forward as a possible consequence of X-ray and gamma ray emissions detected in thunderstorms by airborne and balloon-borne measurements [*Parks et al.*, 1981; *McCarthy and Parks*, 1985]. However, observations of gamma ray radiation in thunderstorms [*Eack et al.*, 1996; *Moore et al.*, 2001] and in a high-voltage laboratory [*Kochkin et al.*, 2015] suggest that this radiation, which may be indicative of runaway electrons, can be produced by lightning leaders, rather than being associated with the initiation phase of lightning. So far, there are no observational data that would support the involvement of any high-energy processes (runaway electrons, X-rays, or gamma rays) in lightning initiation.

Stimulated by the introduction of the "runaway electrons theory," tremendous progress has been achieved in the study and understanding of high-energy atmospheric phenomena. However, the results of these studies have confirmed only a consequential relationship of the lightning processes, characterizing runaway electrons phenomenon as the end result of lightning development, rather than the cause of lightning occurrence [*Dwyer and Uman*, 2014].

Recent observations of the initial parts of lightning flashes at close ranges to the broadband VHF interferometer, the Lightning Mapping Array, and fast and slow antennas for recording electric field changes [*Rison et al.*, 2014] have revealed the sequential occurrence, first of a positive breakdown and then a negative breakdown developing in opposite directions from the same origin of a strong electric field. These dynamics characterized the initial stages of both intracloud and cloud-to-ground flashes. Such unique results constitute the strongest evidence against the runaway electrons theory of lightning initiation and in support of the alternative hypothesis.

They also confirm the validity of the concept of the bidirectional and bipolar leader by *Kasemir* [1950] as the key mechanism of lightning formation.

Testing the runaway electrons theory of lightning initiation in a laboratory is unrealistic, because the runaway mechanism requires breakdown electric fields over distances of up to several kilometers. Testing of the major aspects of the hydrometeor theory, on the other hand, although admittedly a complicated task, is achievable, but has not, until recently, attracted deserved attention from lightning researchers.

There are two interrelated aspects of the hydrometeor theory that need to be considered in laboratory experiments. The first one, the microphysical or environmental aspect, should provide answers to the following questions: (1) What are the realistic sizes, types, and concentration of hydrometeors involved in lightning initiation? (2) What are the ambient electric fields required for leader initiation to occur in the ambient environmental conditions (temperatures and atmospheric pressure) of thunderstorms? (3) How realistic is it to recreate these environmental conditions in the laboratory? The second aspect of the hydrometeor theory, the electrical one, defines the physical mechanism for transition from corona streamers, started either on a single hydrometeor or on a group of hydrometeors, to a leader that becomes a lightning flash.

The reproduction of ambient temperature, pressure, and electric field inside the thunderstorm regions has been previously done only in a chamber of small size. However, the small size of the chamber immediately imposes a limit on the length of the corona streamers obtainable in the experiment, before they attach to the walls of the chamber. Therefore, no experiment in a small environmental chamber can proceed beyond the study of corona formation on hydrometeors. The only alternative is to study the corona-leader transition in a high-voltage environment, from artificial particles that simulate some of the relevant properties of hydrometeors, not from real precipitation particles. This was the objective of the study described in this paper.

The hypothetical process of lightning initiation, as applied to the hydrometeor theory by *Solomon et al*. [2001], in their comparison of hydrometeor theory with runaway electrons theory, consists of conventional breakdown that (to paraphrase their statement) produces avalanches of background electrons, which yield propagating corona streamers. *Solomon et al*. [2001] concluded, although not definitively, that “the conventional breakdown mechanism alone is not a satisfactory explanation of lightning triggering in most cases, while the runaway breakdown mechanism appears more likely.” While the validity of this statement regarding the runaway electrons theory of lightning initiation was shown to be problematic, we agree with the first part of this statement, regarding the weakness of the hydrometeor theory of lightning initiation as producing only propagating corona streamers—just one of several stages in the formation of a leader. In the case of lightning that originates in the cloud, the first (streamer) stage should be followed by the streamer-leader transition and then by the development of a bidirectional and bipolar leader. Without going through these stages, a lightning flash in a thunderstorm cannot occur.

The prediction of lightning inception by large ice particles and extensive air showers, discussed recently in *Dubinova et al*. [2015], attempts to combine the two effects that together may lead to formation of a positive streamer from the ice particles. These effects are the enhancement of the ambient electric field by elongated ice particles of centimeter size and the presence of a sufficiently high number of free electrons provided by RREAs in air showers. If cosmic rays that energize the runaway electron processes are not involved in lightning initiation, then the only other processes leading to lightning initiation (with the exception of God’s will) must be related to hydrometeors. They create thunderstorms, which are the producers of lightning flashes. Defining the physical mechanism of lightning initiation is an enormously difficult task, which should be approached only in incremental steps. In this study, we try to address one of these steps and to bring to bear this knowledge for future research.

2. Considerations for the Experiment

The possibility of corona streamers starting on individual hydrometeors is affected by the field-enhancement factor of a particle’s shape (e.g., for a spherical particle, this factor is 3) that magnifies the ambient electric field on the surface of the particle. This field should be sufficiently high to sustain creation of the multitude of streamers necessary to produce the streamer-leader transition. *Lalande et al*. [2002] have shown that the electric field at the hydrometeor surface should be 2 orders of magnitude higher than the internal field of a forming leader (made of conductive plasma), in order for the streamer-leader transition to continue.

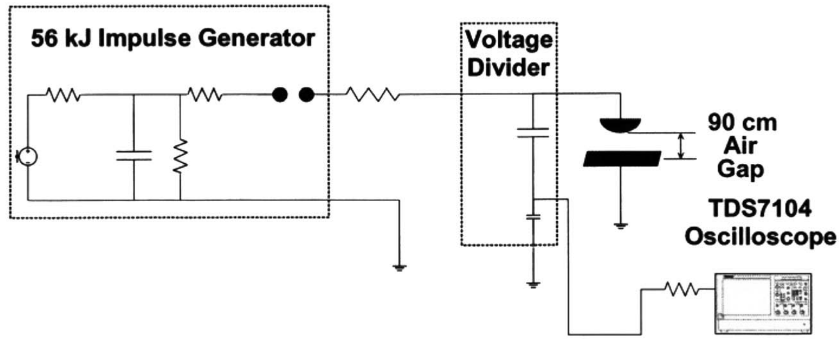

Figure 1. Diagram of the measurement system for the test gap in the high-voltage facility of the Mississippi State University.

Hydrometeors with shapes that can create very high field enhancements are not often found among cloud particles. Therefore, we believe this may be a reason why a streamer-leader transition that starts on a single ice particle (within a cluster of widely spaced particles in a cloud) is probably an unrealistic scenario.

However, hydrometeors in the cloud are of different densities, even appearing in closely spaced clusters (arrays) of particles of similar sizes (e.g., ice crystals), or mixed sizes (e.g., hail and graupel). *Gardher et al*. [1985] reported, from airborne measurements in summer thunderstorms, that graupels "in sizes from $<$100 μm to $>$1 mm, are in total concentrations ranging from 2 to 40 L^{-1}." From measurements with a sailplane, at altitudes from 7 to 9 km and radar reflectivity from 20 to 45 dbZ, *Dye et al*. [1986] reported that "as the cloud evolves to a mature stage of microphysical development, the total ice particle concentration can increase up to several hundreds per liter." The references to *Gardher et al*. [1985] and *Dye et al*. [1986] support the assumption of close clusters of hydrometeors, which are the object of our study. Their observations, however, do not represent the state of hydrometeors in regions of lightning initiation. The assumption we were using in our laboratory experiment of the spacing of a few centimeters between particles seems plausible, although not yet verified by in situ measurements. To our knowledge, there are no in situ measurements of hydrometeor sizes and concentration in the regions of lightning initiation during the electrically active stage of thunderstorms. To acquire such measurements would be too dangerous for any flying platform with on board sensors.

The suggestion that lightning initiation should be affected by closely spaced clusters of hydrometeors was first discussed by *Nguyen and Michnovsky* [1996]. With this idea in mind, our expectation was that the behavior of such closely spaced arrays of particles in a uniform electric field in the laboratory might provide an important clue to the understanding of the effect of a hydrometeor array on the streamer-leader transition in the regions of lightning initiation in the cloud.

We expected that corona streamers could easily bridge the gaps of a few centimeters between the suspended particles placed in a strong ambient electric field. We also postulated that an array of particles might behave as the equivalent of a single large, weakly conductive-and-charged body, which would have a total field-enhancement factor significantly greater than that of any individual particle. From such a body, suspended in an ambient electric field of realistic values, the bipolar and bidirectional leader may emerge. An experimental testing of this hypothesis was also the objective of this study.

Field observations of the locations in which lightning originates in storms, conducted with both the time-of-arrival technique and interferometers for mapping lightning-radiation sources [see, e.g., *Proctor*, 1991; *Shao and Krehbiel*, 1996], show that lightning initiation occurs primarily in three thunderstorm regions, centered roughly at −10°C, −20°C, and −40°C. Two of these three regions have temperatures cooler than the so-called "reversal temperature" of ~20°C, believed to be the lowest temperature possible for streamer formation on a frozen particle [*Griffiths and Latham*, 1974]. Later on, J. Latham (personal communication, 2003) expressed some reservations about the conclusions of their earlier study. Also, in laboratory investigations of streamer formation from simulated ice particles, *Petersen et al*. [2006] and *Petersen et al*. [2014] found streamers to occur at temperatures as low as −38°C, basically confirming the findings from lightning-radiation-source mapping.

Despite the differences in environmental and electrical conditions in all three storm regions where lightning initiates, the common types of hydrometeors there are ice particles, either graupel or hail, or ice crystals. Thunderstorm observations with dual-polarization radar have shown that in severe (lightning producing)

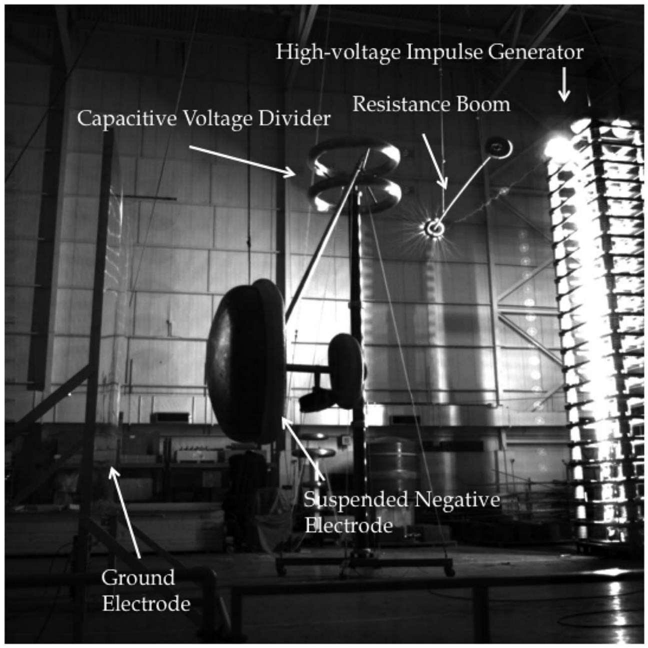

Figure 2. Setup of the first phase of the experiment in the high-voltage facility. The electric field in the gap is horizontal, and particles of the array are suspended vertically, as seen in Figure 3. The resistance boom is connected to both the impulse generator and voltage divider.

thunderstorms, hail particles prevail above the altitude of 5 km to the top; below that level they are mixed with rain [*Zrnic et al*., 2000]. For this reason, in our laboratory array of particles, we simulated larger-sized ice particles (hail) and the spacing between them, by using hollow aluminum balls of ¾″ diameter. Of course, hail is not a pure dielectric, due to the impurities it contains, and it is also not a perfect conductor, like aluminum balls. Another important difference between metal balls and ice particles is the secondary emission of electrons when ions impact a metallic surface, which does not occurs with ice. Therefore, an experiment with metal balls as substitutes for hail may be used only to investigate the array's effect on the formation of a leader. With the limited length of the gap between electrodes, it was not possible to separately evaluate the role of the number of particles and their geometrical arrangements. The effects of other properties (e.g., conductivity and charges) of hail particles, besides their sizes and numbers in an array should perhaps be evaluated in future experiments.

3. Setup of the Experiment

The experiment was conducted in the high-voltage facility of the Department of Electrical and Computer Engineering at Mississippi State University. The 56 kJ impulse generator of this facility is capable of producing a maximum voltage of ~2.4 MV. During the first phase of the experiment, in 2013, we hoped to reproduce streamer formation followed by streamer-leader transition from an array of uncharged conducting particles suspended in the gap between the high-voltage and ground electrodes, in an ambient E field of 1 MV m^{-1}. At normal atmospheric conditions, an electric field of this magnitude is sufficient to lead to electrical breakdown from the surface of spherical particles. A uniform E field of 1 MV m^{-1} was produced in a 0.9 m long gap by an impulse generator that charged the resistance-capacitance circuit that consisted of a capacitive voltage divider, $C = 540$ pF, and a water resistance boom, $R = 55$ kohm (see Figures 1 and 2). The time constant of the RC circuit was ~30 μs.

Figure 3. Three metal balls of ¾″ diameter separated by ¾″ spacing and suspended in a uniform E field of 1 MV m^{-1} between the negative high voltage (on the right) and the ground electrodes (on the left).

In addition to measurements of the applied voltage and current to ground, during the first stage of the experiment we used a high-speed video camera Photron SA 1.1, operated at a speed of 360,000–450,000 fps. The current to ground was measured using a current transformer. The negative electrode

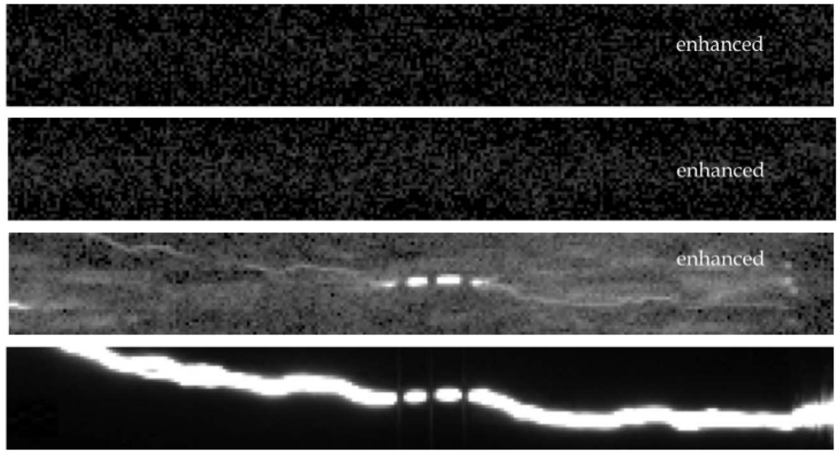

Figure 4. Stages of the discharge formation between three metal balls separated by gaps equal to their diameter of 3/4″. Sequential video frames start from the top to downward: The speed of video recording is 360,000 fps, with 1 μs of exposure time, and 1.8 μs of the interval between frames.

was a metal cup 6 ft in diameter, with a smooth spherical frontal surface of 5.65 ft radius. A thin layer of electrically conductive grease (Noalox) was applied to the entire surface of the negative electrode. The ground electrode was made of three 3 × 12 ft aluminum sheets fastened to the wooden frame.

The criterion for triggering both high-speed video systems used in our experiments was a current pulse during the flashover. The trigger signal from the oscilloscope was connected to the external trigger port of the video system with a pretrigger option available. The pretrigger option was a critical feature for our observations.

The hollow metal balls on vertical Teflon threads, which were secured to two polyvinyl chloride pipes at the top and the bottom of the ground electrode, were placed in the uniform E field at about half width of the 90 cm gap between the high-voltage and ground electrodes (see Figure 3).

4. First-Phase Results

In the course of the tests, the negative polarity voltage from the impulse generator (applied to the high-voltage electrode) grew exponentially until the flashover of a discharge within the gap connected both electrodes. In the beginning of a series of tests with different configurations of balls suspended in the gap between electrodes, we conducted a test without placing any balls in the gap. The results of these tests were negative during both stages of the experiment, the first in 2013 and the second in 2014. This brought us to the conclusion that neither streamers nor a space leader occurs in the gap between electrodes of the given shapes and at the given magnitudes of applied voltages.

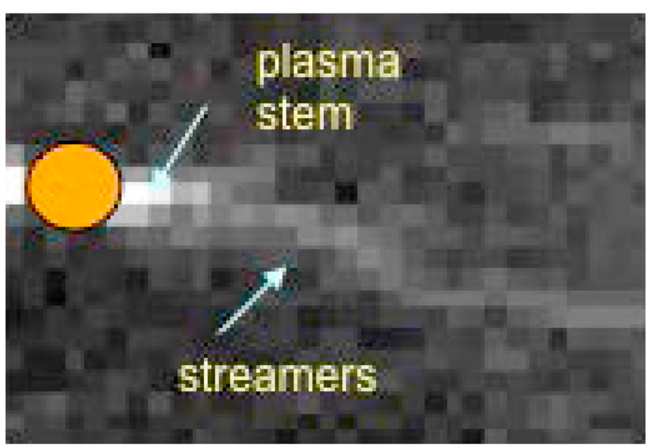

Figure 5. A plasma stem that formed at the outer edge of the outer ball and the multitude of streamers in the surrounding space. The ball is marked by a circle.

As anticipated, a plasma channel formed between the conductive particles at the ambient E field, which was one third of the breakdown E field at normal atmospheric conditions (3 MV m^{-1}), and developed bidirectionally, with positive and negative streamers emanating from the outer sides of the balls in the array (Figure 4).

The four subsequent video frames in Figure 4 show the formation of the

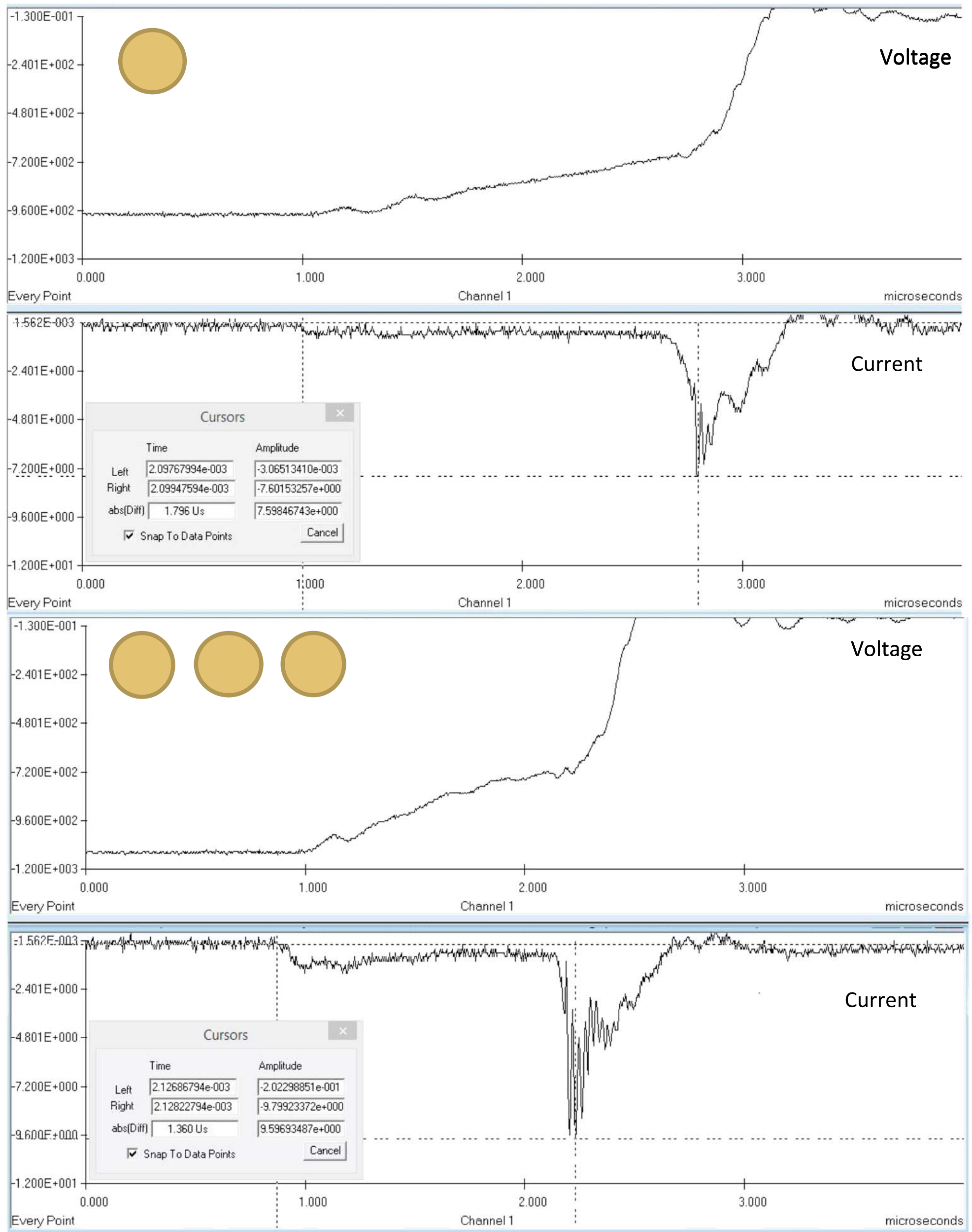

Figure 6. Comparison of breakdown conditions for a single ball and a three-ball array (see symbols). The top part of each panel shows voltage, $V(t)$, in kV, and the bottom part shows current, $I(t)$, in kA, prior to the flashover. The two vertical dashed lines in the graph for current identify the period, *delta T*, of rising voltage between occurrence of the first streamers and the beginning of the flashover, which is the duration of the discharge: 1.8 μs for a single ball and 1.36 μs for the three-ball array. The voltage units are in kV, and the current units are in kA.

plasma channel from three balls separated by the diameter size gaps (see Figure 3). The first two frames of the sequence are absolutely dark, even after image enhancement—an indication of the absence of any streamers prior to the third frame. During the third frame, the fuzzy images of numerous streamers fill the space between the electrodes, and a bright, luminous plasma channel is visible between the balls. Also clearly seen are plasma stems at the outer edges of the left and right balls (see Figure 5)—all taking place during a single-frame exposure of 1 μs. The fourth frame, in Figure 4, depicts the flashover that occurs when the bidirectional leader reaches the opposite electrodes.

Figure 7. Setup for the second phase of the experiment at the high-voltage facility at Mississippi State University. The ambient E field between the upper negative and the lower ground electrodes in the 0.9 m wide gap is vertical; the particles were suspended on horizontal dielectric threads.

The sequence of video images in Figure 4 was a lucky occurrence, because in most other events of this type the Photron SA 1.1 camera captured only the images of the flashover. The reason for this is that the streamer-leader transition phase did occur during the 1.8 μs long time intervals between video frames, rather than during the frame-exposure time of 1 μs. Obviously, we needed a much faster speed of video recording in order to capture this transition. Therefore, unfortunately, an accurate visual interpretation of the records obtained at the first stage of the experiment, beyond the lucky case presented in Figure 4, was not possible. Due to the insufficient speed of the video recording, we had no means of postulating which form of the discharge (streamers or the arc channel between balls) started first; confirmation came during the second phase of the experiment.

The time variation of both the voltage in the gap between electrodes and the current to ground, prior to the flashover (the attachment of the plasma channel to both electrodes), is presented in Figure 6 for two tested cases: with a single ball and with three-aligned balls, as seen in Figure 3. In Figure 6, $t = 0$ is the beginning of the last 4 μs long segment of the total record length of about 200 μs, from the moment of firing the impulse generator. We identify the beginning of the discharge with the rise in voltage and current to ground that precedes the flashover. The peak amplitude of the current to ground marks the ending of the discharge. A comparison of the two sets of records in Figure 6 indicates that the duration of the discharge is shorter for the three-ball array (1.36 μs) than for the single ball (1.8 μs). From the record for the case of two balls (not shown here), the duration of the discharge was 1.64 μs. The consistent difference in durations of discharge suggests a faster development of the leader phase for the larger array of particles.

During the discharge formation, the current to ground was steady at an amplitude of 400 A, for the case of the single ball and two balls, but in the case of the three-ball array it deepened initially to a maximum value of 1.2 kA, settled for a while at the level of 600 A, and then became steady at 400 A level.

We did not consider the results obtained during the first phase of the experiment as statistically significant, because we had a rather limited period of access to the high-voltage facility for more testing. However, the trends noticed in the durations of discharges and current to ground seemed consistent and significant, and therefore, required verification during the next phase of the experiment.

5. Second-Phase Results

From the experience of the first phase of the study, in 2013, we learned that the total duration of the discharge is less than 2 μs, which indicated the need to use a speed of video recording greater than 2 Mfps, in order to be able to observe the streamer-leader transition from the array of particles in more than one video frame.

During the second phase of the experiment at the same high-voltage facility, in 2014 (Figure 7), by adding more hollow metal balls, we tested several different spatial arrangements of the conducting particles in the array. For high-speed video observations during this phase, we employed the HPV-X high-speed video camera made by Shimadzu Scientific Instruments, which has the recording speed of 10 Mfps, a continuous recording capability of 256 frames maximum, at 10 bits, and an exposure time

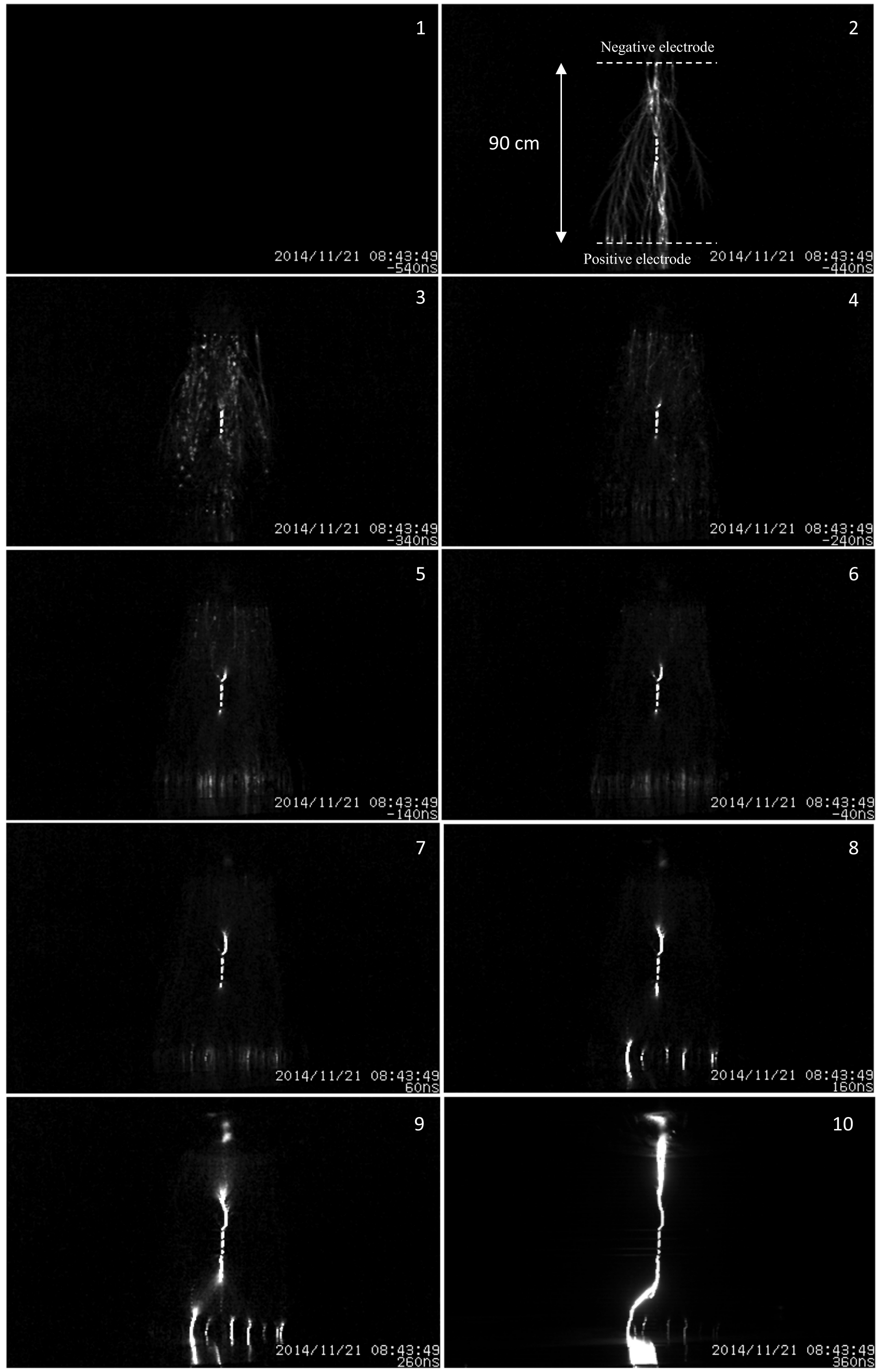

Figure 8. Sequence of video frames of the developing discharge from four aligned metal balls of ¾″ diameter each, suspended in a 0.9 m gap between the upper negative and the lower ground electrodes. The gaps between the balls are (from top to bottom) 3/4″, 1 1/2″, and 3/4″. The duration of the discharge is ~800 ns. The exposure time is 50 ns. All images, except the last one, are enhanced to the same level of light intensity.

of 50 ns at 10 Mfps. Extremely valuable for our experiment was the camera pretrigger feature that allowed us to set up an external trigger point on any of 256 recorded video frames. We set a pretrigger time of 3 μs, i.e., 30 video frames prior to the beginning of a flashover, with the triggering signal provided from the oscilloscope at the rising front of the current pulse of the flashover.

Table 1. Parameters of Discharges Obtained in the Second Phase of the Experiment

Configuration of the Linearly Arranged Array of Balls	Maximum Voltage (MV)	Discharge Starting Time (ns)	Flashover Time (ns)	Discharge Duration (μs)
Two metal balls	No record	−450	850	1.3
Three metal balls	−1.232	−440	560	1.0
Four metal balls	−1.152	−440	360	0.8

During the second phase of the experiment, we tested arrays of aligned particles made of two, three, and four hollow metal balls, with distances between particles equal to one and two diameters, and one array made of five hollow balls, with two particles aligned and four of them forming a rhomb.

The sequence of video frames of the discharge from the array of four vertically aligned balls, obtained with the HPV-X high-speed video camera, is shown in Figure 8. We used the image-intensity adjustment, for images in Figure 8, to expose the images of streamers, which would otherwise be almost invisible. This image adjustment made it possible to see both streamers and leaders in their developments, rather than "washing out" the differences between them.

The description of the discharge process depicted in Figure 8 characterizes each configuration of the arrays, regardless of the number of balls and their arrangement in the array. All discharges exhibited from the very beginning (the first video frame with an image) a strong burst of branched negative streamers that apparently originated at the negative electrode and fanned out toward the ground electrode. Simultaneously, a plasma channel extended between all suspended balls (see frame at −440 ns), and the plasma stems at the outer edges of the outer balls of the array were clearly visible. However, no positive streamers from the ground electrode were observed during this time. They did appear hundreds of nanoseconds later (see frame at −140 ns). The number of negative streamers decreased with time, while the plasma channel was developing upward and unidirectionally as a positively charged leader, starting with frame at −240 ns. The development of the negatively charged leader from the array toward the ground plate was delayed by ~400 ns after the start of the upward positively charged leader. It did occur simultaneously with the appearance of multiple, nonbranching positive leaders from the ground electrode (see frame of 160 ns).

Unfortunately, the high-resolution records of voltage and current to ground at the second stage of the experiment were recorded with a wrong sampling rate, so they became unusable for evaluation of voltage and current records of discharges lasting less than 2 μs. In the absence of such records, we analyzed in Table 1 the findings from video observations. The data in Table 1 confirm the findings of the first stage of the experiment, namely the effect of the number of particles in the array on the duration of the discharge: the larger the array, the shorter the duration of the discharge within the same gap length between electrodes. This finding also points to a higher speed of propagation, and, thus, a stronger current in the plasma channel formed from the larger array, an indication of which is seen in a comparison of the two current records in Figure 6, which were obtained during the first stage of the experiment. (A different experimental setup at each stage may contribute to some differences in the results.)

A key question to address in an experiment like ours would be how the array's size (the number of particles and spacing between them) influences the maximum voltage needed to start the discharge. In order to investigate this issue, one would need a much wider range of array sizes and also multiple tests for each size of the array.

6. Concluding Remarks

By using an array of conducting particles in a high-voltage environment, we achieved an accurate laboratory simulation of the conditions that can lead to an electrodeless discharge initiation from an array of particles. Placed in an ambient E field that was sufficient to start breakdown on a single-conducting particle, the array of particles became a conductive and charged body, from which the bidirectional and bipolar leader developed. The size of the array affected the duration of the discharge and the magnitude of the arc current, making shorter the duration and increasing the current. In our experiment, we, however, were not able to isolate the influence of the shape of the array from its size in the numbers of balls.

There are significant differences in the electrical properties of a hail particle and a metal ball, such as conductivity and capacitance; the similarities are only the dimensions of each, which they share. This is why the streamer-leader transition and formation of a bidirectional, bipolar leader occur (as we observed) from a single metal ball but would not occur from a single hail particle. On the other hand, corona formation from a single hail particle is possible and has been observed in laboratory experiments [e.g., *Petersen et al*., 2006].

The structure of the negative streamers from the negative electrode, at the very beginning of the discharge in our experiment, resembled that of negative streamers from a pointed negative electrode in a high-voltage facility [*Kochkin et al*., 2014], with one important exception: Negative leaders that start either from a pointed electrode or from the tip of the existing negative leader develop a so-called space leader, which we did not observe in our experiment where the negative electrode was nearly flat in configuration. The appearance of streamers, first from the high voltage and then from ground electrodes during a discharge in a high-voltage laboratory, may not exist in a cloud. (These streamers did not, however, mask the stages of leader development from the array of balls.)

The key question, which we were unable to resolve, is which of two processes—negative streamers from the HV electrode or the plasma channel that connects the balls—started first. There was no evidence, in either stage of our experiment, of the occurrence of primary streamers from the negative electrode at any time prior to the first video frames, where they are seen together with the plasma channel that connects the balls.

The only way to remove the electrode effects from the experiment like ours would be to create artificially a charged cloud with the potential of several MV and to suspend particles in this cloud. The use of artificial clouds of charged-water aerosol for investigation of the physics of lightning [*Temnikov*, 2012] is a clever and promising technique to address the same issues that drove our experiments.

The testing of the hydrometeor theory of lightning initiation in a high electric field environment should be continued, first, for confirmation of the results of our study with statistically significant data and also for conducting tests of particles closely resembling hail in its conductivity and charges. In solving the mystery of lightning initiation by hydrometeors, we may find that an array of particles might behave as the equivalent of a single large, weakly conductive-and-charged body, which would have a total field enhancement factor significantly greater than that of any individual particle. This charged volume may serve as the nucleus from which the streamer-leader transition and the bidirectional, bipolar leader initiation in a strong ambient electric field may occur.

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