PLASMA FILAMENT INVESTIGATIONS

USING HIGH SPEED VIDEO IMAGING

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Plasma Filament Investigations Using High Speed Photography. Stephen Anderson (Bethel College, Saint Paul, MN, 55112) Andrew Post Zwicker (Princeton Plasma Physics Laboratory, Princeton, NJ, 0543).

A Jacob's ladder apparatus and a plasma ball are two tools that are used to study plasmas in an educational setting. However, much of the physics behind these beautiful plasmas remain unknown or not well studied. A new way to examine these plasmas is through high-speed video imaging. We used a Canadian Photonic Labs Mega Speed 1000 camera to view behavior such as filament movement, fragmentation and recombination with other filaments at speeds at over 8500 frames per second. Analyzing our movies in slow motion, and through the aid of image processing software, we are able to trace each step of this behavior and quantify values such as filament brightness and thickness. Along with spectroscopic techniques, we infer basic plasma parameters and attempt to fully explain the physics controlling each source.

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1. INTRODUCTION

A plasma ball and a Jacob's ladder apparatus are two fascinating plasma sources that amaze peoples in movies, decorate homes, and even help people learn about the fourth state of matter. While these devices have been around for quite some time there is still much that can be learned from them. The goal of this paper is to unlock some of the mystery embedded in these beautiful plasmas. Besides basic information on how these devices work, an in depth study of how the plasma itself moves, forms, and dies is presented. One new tool that is used to study these subjects is a high-speed video camera. The camera we used allowed us to take pictures as fast as 8500 frames per second. Besides producing some amazing movies, this technique allows us to study the exotic movements of the plasma filaments on a frame-by-frame basis.

The camera is a good tool because it allows us to view behavior that one could not catch with his naked eye. A sample of such phenomena that we explain in this paper are: intensity variations in the plasma filaments, zigzag motion of the plasma ascending Jacob's Ladder, and lightning like streamer branching in the plasma ball. However, before we look deeper into these behaviors, we must first understand the subjects we are studying along with the physics that drive them.

2. BACKGROUND

2.1 Jacob's Ladder

Figure 1. A Jacob's Ladder Apparatus

Figure 1. shows our Jacob's ladder apparatus. The device consists of two conducting wires connected to the secondary of a high voltage transformer. One of the best places to see a Jacob's ladder in action is to watch old horror movies. One will undoubtedly see one arcing away in the background of the evil scientist's lab.

The type of plasma that a Jacob's ladder produces is an arc. In order to initiate an arc, the gas between the electrodes needs to become ionized so that current can flow. In general, there are three ways in which this initiation can occur: initial electrode contact, pre-ionization, and high-voltage breakdown. In the he first method, a cathode and an anode are brought together and short the circuit until a temperature is reached where thermionic emission is possible. As a result of the electrons being released, the material of electrode is ionized and serves as a charge carrier between the electrodes after they are drawn apart [2]. A second way to initiate an arc is to ionize the gas between the electrodes prior to striking an arc. This is done by introducing a secondary plasma, which provides the necessary charge carriers. The third method, high-voltage breakdown, describes how the plasmas in both the Jacob's ladder and a plasma ball are initiated.

High voltage breakdown in a Jacob's ladder apparatus starts at the anode wire. When the electric field in the gas around the anode is high enough, an event known as an electron avalanche occurs which results in a glow discharge around the anode [3]. This electron avalanche is initiated by a "foreign" electron that could come from a cosmic ray or from an experimenter shining a UV light on the subject [4]. This stray electron is energized by the electric field from the anode. If this energy is high enough, the electron ionizes a molecule of the surrounding gas. At this point the original electron has lost its energy freeing a second electron. However, now we have two free electrons. These two electrons are then energized by the electric field and ionize two more molecules, resulting in four free electrons; soon one sees why the name avalanche is used. This avalanche is eventually limited by electron energy loss and through loss of the electrons themselves due to recombination with ions and other ways [4]. One result of this process is a stable glow around the anode. However, if the avalanche is larger and more concentrated around the tip of the anode, a positively charged head will form. This head is smaller (more pointed) than the anode and thus has a stronger field [3]. An arc grows as this head moves across toward the cathode ionizing the gas along the way. Unfortunately we cannot achieve speeds high enough to catch such behavior as it occurs on a nanosecond time scale[3].

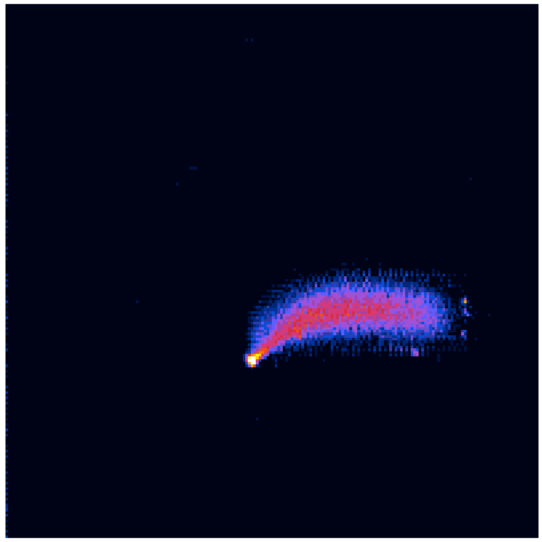

Figure 2. A Jacob's Ladder Arc
(Color Enhanced)

Figure 2. is a color-enhanced picture of a fully developed Jacob's ladder arc. The white spot on the left is a hot spot. A hot spot on an electrode is a result of high current density. These spots are hot enough to achieve the thermionic emission as described earlier [4].

In order for high-voltage breakdown to occur, certain conditions must be met. The voltage necessary for breakdown of a gas is proportional to the distance between the electrodes and to pressure. For gaps on the order of a few centimeters, breakdown voltage is around 32kV per centimeter at 1 atm [4]. The analysis section of this paper will show how this relationship helps describe what is going on in the Jacob's ladder.

2.2 Plasma Ball

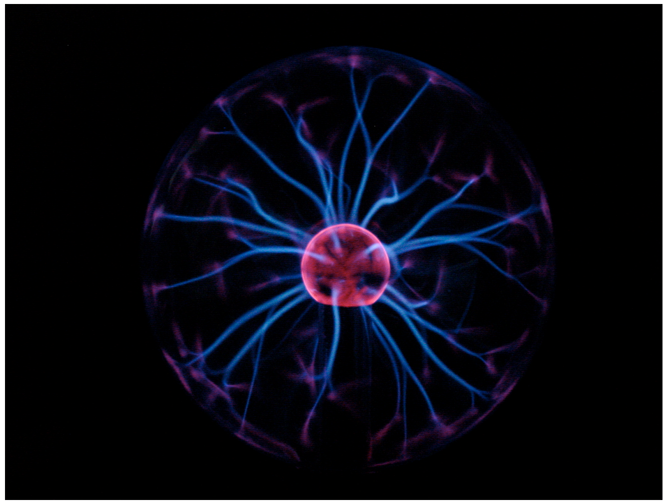

Figure 3. A Plasma Ball

Figure 3. shows the plasma ball we used in our experiment. The best place to start in understanding how it works is the inner electrode, located in the inner glass-covered sphere. A wire coming from the high-voltage and high-frequency power supply in the base of the plasma ball is attached to a sphere of steel wool located inside this inner sphere. The steel wool is there to provide a non-uniform electric field for the plasma streamers to form in. This happens as different strands in the mess of steel wool accumulate enough charge to form a streamer. With only one electrode, capacitance through the air provides the connection to the glass sphere. This is what allows the streamer to travel from the inner electrode to the outer glass sphere. When a person touches the outer sphere or another conductor comes into contact with it, the current follows this path to ground.

The gas inside the larger main sphere is at a lower pressure than the air outside it (typically 2 to 7 torr)[1]. This is necessary in creating streamers over larger distances at relatively low voltages. In order to make the plasma ball safe, the voltage is driven at high frequencies (tens of kilohertz). In doing so, the current is not able to penetrate the skin deep enough to cause harm.

The way a streamer is formed in a plasma ball is similar to the way an arc is formed in a Jacob's ladder. In an arc, the temperatures are much higher at the electrodes as can be seen in the hot spots. This is due to the fact that more current is needed in the breakdown process at higher pressures such as the Jacob's ladder. In the case of the plasma ball, the pressure inside the globe is less. Instead of an arc, which has a higher current density, streamers form. A streamer is defined as a channel of weakly ionized gas that forms from the primary avalanche whose process is described in the discussion of the Jacob's ladder. A streamer can form on one or both of the electrodes [4]. One way in which this avalanche to streamer process is thought to take place is through photoionization [4]. In this process, the primary avalanche excites nearby atoms resulting in photon release. These photons ionize additional molecules not reached by the primary avalanche. Electrons resulting from this ionization process produce a secondary avalanche. These electrons fill in behind the head of the streamer and combine with the positive ions left over from the primary avalanche. The result is a conducting, quasineutral plasma that makes up the streamer [4].

3. PROCEDURE

3.1 Camera Setup

The camera we used in our experiments was a Canadian Photonic Labs Mega Speed 1000. It is a black and white CCD camera that is controlled by a personal computer. The camera increases speed by scanning a smaller area of the CCD. In other words, the faster we wish to go, the smaller image size we must deal with. The slowest rate we use to study our plasmas is 194 frames per second. This corresponds to an image size of 640x 476 pixels. The other limitation of the camera is that as the speed increases, less photons are absorbed results in a dimmer image. In order to counter this problem we adjust the f-stop of the camera to let in more light, or use an electronic gain in the software of the camera to amplify the signal. However, even with these ways of amplifying the light, the fastest we were able to gather useful information for our particular subjects was a slightly under 4000 frames per second. With this in mind, a way to increase speed would be to develop brighter sources. On the other hand, we also had to be careful not to overexpose the CCD, as this would 'washout' the brightest parts in the image resulting in imprecise data. While taking our images, both the camera and the subject were covered with a black hood to minimize light pollution from lights in the lab as well as reflections off of the glass of our subjects.

3.2 Plasma Ball Experimentation

Figure 4. shows one of the setups for taking pictures of the plasma ball. This particular globe's frequency is 25 kHz. The inner sphere diameter is 4 cm and the outer globe diameter is 20 cm. Initially, we recorded the conditions of the lab and simply turned on the camera and tried to see what we could see. While the images we obtained were very beautiful, they were difficult to interpret. The main reason was because the

movie is a two dimensional interpretation of a three dimensional world. We wanted to study intensity, but this would be near impossible since a streamer moves toward and away from the camera as well as up and down, giving false intensity readings. The way this was solved was to attach a metal electrode to the outside of the glass sphere. As described earlier, a plasma streamer will be drawn to this electrode since it provides a better path to ground than the air around it. Since the electrode was stationary, we had a streamer that was ``tied down'' on both ends. This more or less forced the streamer to stay within a two dimensional plane. This is not to say the streamer did not drift in and out at all, but it was a significant improvement.

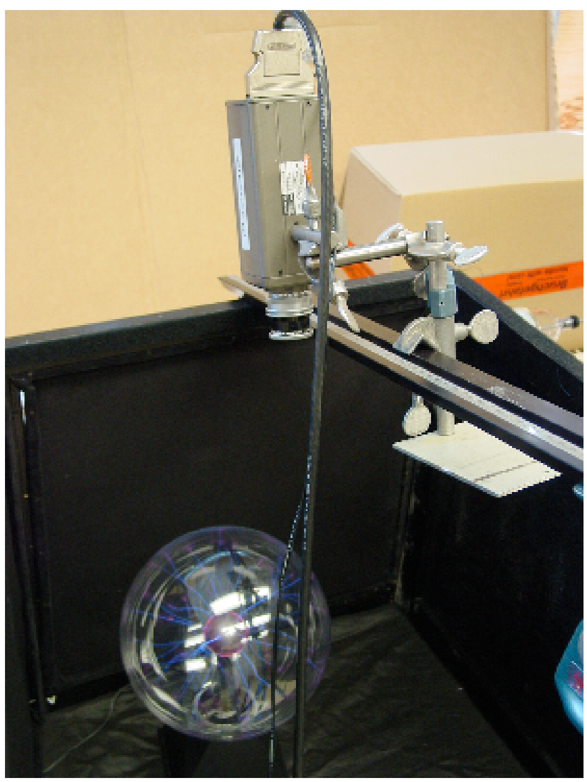

Figure 4. Plasma Globe Setup.

3.3 Jacob's Ladder Experimentation

Figure 5. Jacob's Ladder Setup.

The Jacob's ladder setup we used (Fig. 5) is surrounded by plastic for protection. Not only did this protect its users, it stopped any exterior air currents from interfering with the experiment.   The power supply was taken from a neon sign. It contained a transformer with a primary of 115V and a secondary of 15 kV. The current alternated at 60 Hz. The distance between the wires on our Jacob's ladder varied from .5 cm on the bottom, to 3 cm on the top where the wires ended.

One problem we ran into with the Jacob's ladder is that it interfered with the electronics in the camera. In order to alleviate this problem we built a Faraday cage around the camera using a grounded copper mesh.

4. ANALYSIS AND RESULTS

To analyze our data, we look at single pictures instead of analyzing the movies themselves. For instance, after a run at 1,100 frames per second, we get 654 individual snapshots during a timeframe of .86 ms. To analyze our images, we used Scion Corporation's *Image* software. This program allows us to put an *x, y, I* coordinate system, with *x* and *y* representing position, and *I* representing intensity. It also allows us to assign colors to the black and white pictures, making them easier to analyze.

4.1 Plasma Ball Analysis

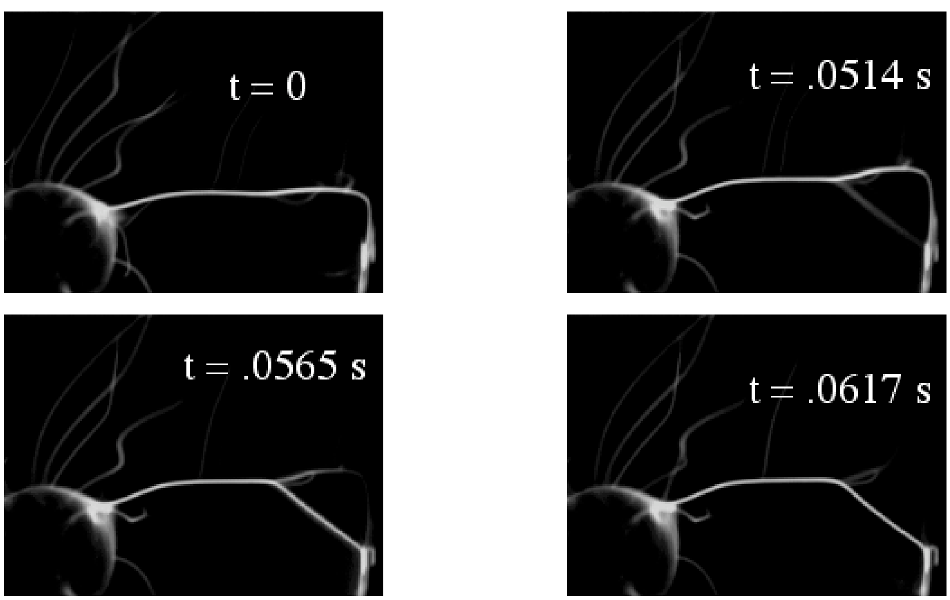

Figure 6. Plasma Ball Streamer Branching Event.

Upon viewing movies of the plasma ball, one of the first behaviors that stands out is streamer branching. Figure 6. shows an example of this behavior. The bright spot on the right is the metal electrode attached to the side of the sphere to minimize three-dimensional problems. Through the progression of these four images, the streamer rises, and a shorter path to the anode is found as a streamer forms along this path. When the connection is made, the current follows this new shorter path. Such an event is reminiscent of lightning and how it seeks the shortest path to ground by branching out and forming streamers.

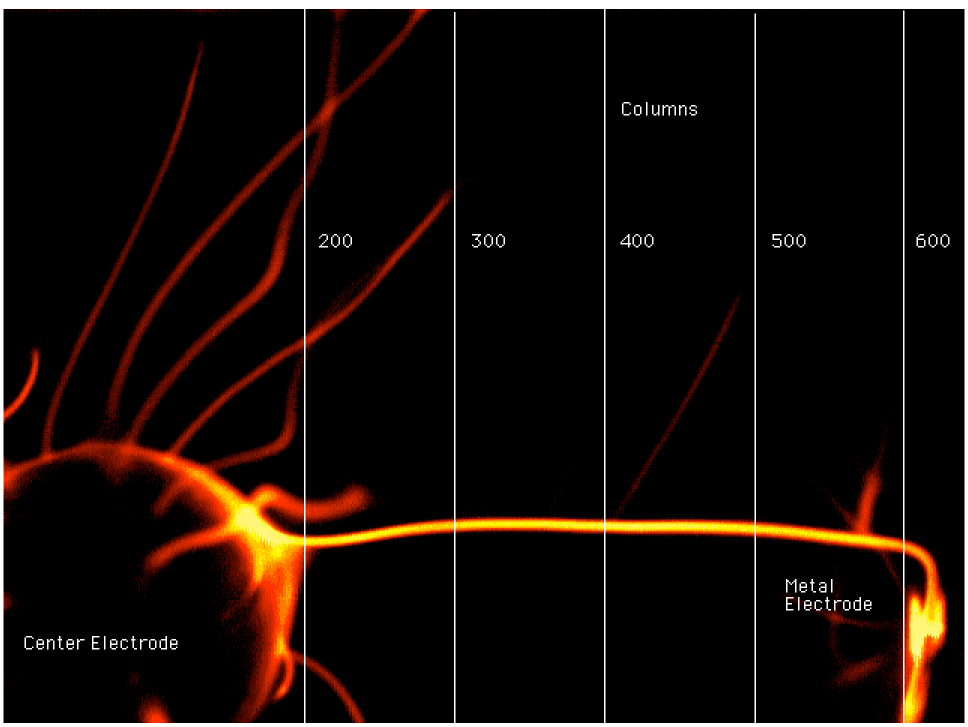

Figure 7. Data Taking Method For Plasma Ball Streamers.

Another aspect we study is the position of the streamer as it rises. To do this we recorded y positions along various x columns in the image. Figure 7. gives an example of this method. Figure 8. shows position of the streamer's brightest point along the various *x* columns. One notices that while the slope of the points along column number 400 is close to linear while the others are not. This is due to the fact that this column is in the middle of the streamer so it can move with less restriction. Along the other columns, the plasma is 'tied down' to the electrodes and cannot rise at the same rate as the middle column. Using the slope of this middle column, we calculated the maximum speed that the streamer is rising is 73.564 mm/s.

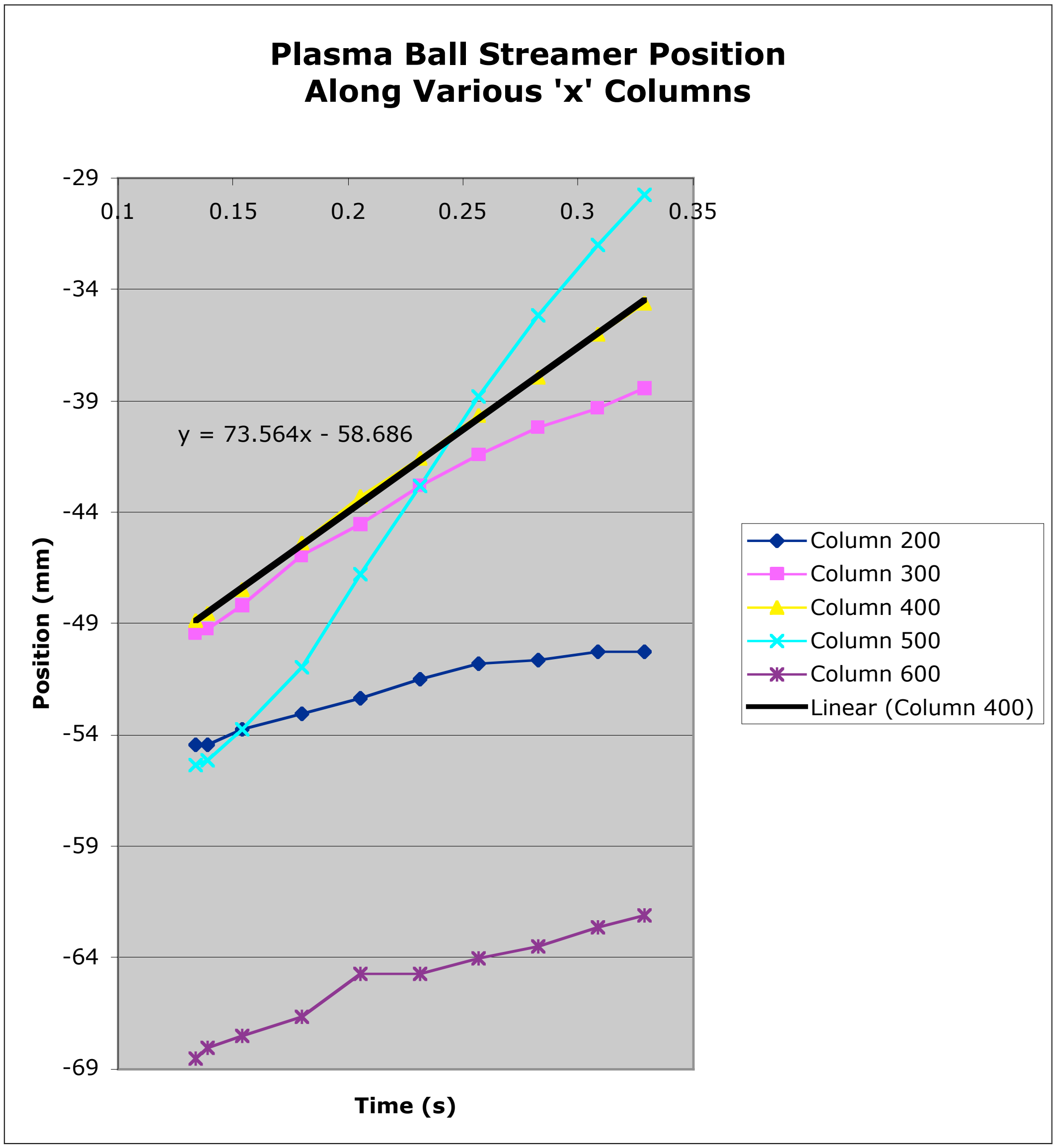

Figure 8. Position of Plasma Ball Streamer

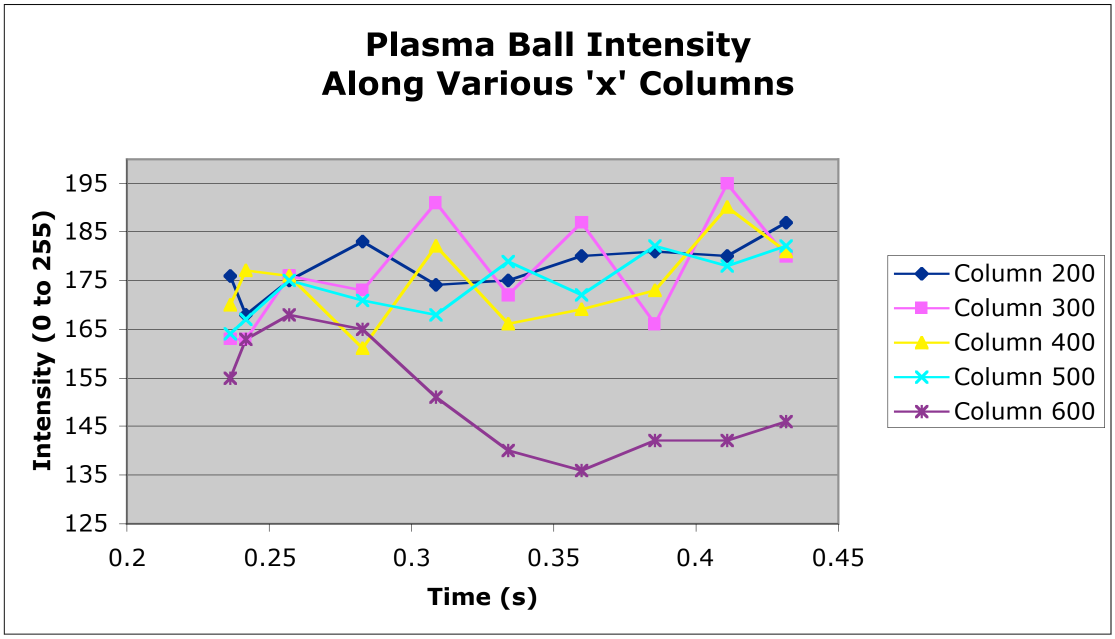

Figure 9. Intensity as a Function of Time

Figure 9. shows the intensity along these same columns as a function of time. The observed fluctuations may be due to the streamer wandering back and forth ever so slightly. Again this is the three dimensional problem discussed earlier. In general, the streamer along columns 200 to 500 is relatively uniform. The reason intensity along 600 is not uniform is because in the between .25 s and .3 s the hotspot of the metal electrode that was attached to the ball had wandered a bit into column 600 where it usually is not located. This gave much higher intensity readings along the 600 column.

4.2 Jacob's Ladder Analysis

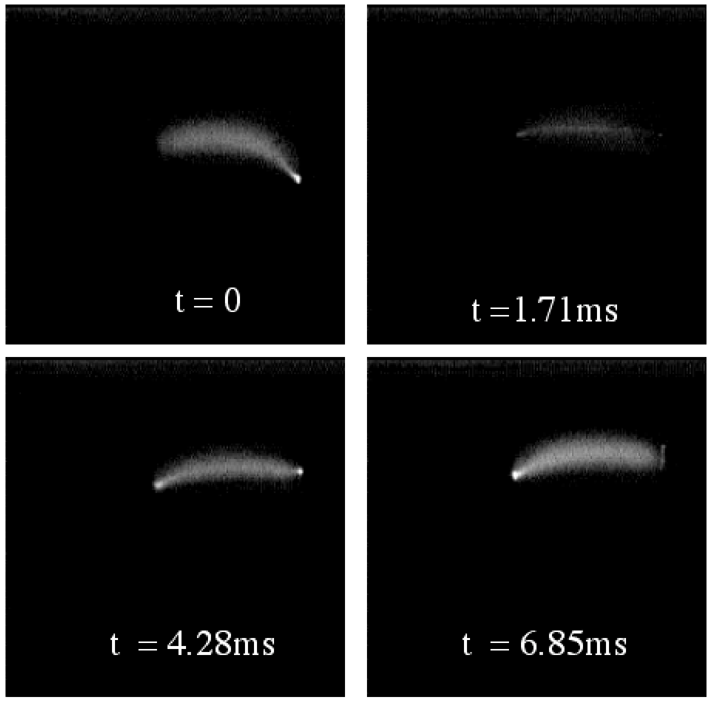

Figure 10. Evolution of a Jacob's Ladder Arc

Time (ms)	*Position of Hot Spot*
0	X
1.71262	Left
5.13786	X
6.85048	Right
15.41358	Left
23.97668	Right
30.82716	X
32.53978	Left

Table 1. Jacob's Ladder Hot Spot Position Over time

Watching a high speed movie of a Jacob's ladder, one notices that it exhibits a zigzag motion as it climbs the wires, similar to the way a person climbs a ladder. Figure 10. shows the hot spot move from left to right as the arc rises. Table 1. shows the position of the hot spot over time. In this table, *X* represents a transition stage between left and right. Notice that there are times where the camera does not catch this transition.

Column Number	*Speed (m/s)*
400	.53
450	.31
500	.27

Table 2. Jacob's Ladder Rise Speeds

Table 2 shows the speed at which the Jacob's ladder plasma rises along various x columns. The speed of the arc closest to the wires, along columns 400 and 500, are off by a factor of nearly 2. One would think that these speeds should be the same and that the speed in the middle column is the fastest as it was in the plasma ball. The reason for such a high speed along column 400 may be due to a higher temperature hot spot on that side. Another observation is that the arc is varying in intensity. Figure11. shows the intensity of the light of the arc as it rises over time. Looking at this rough data, it is clear, and not surprising that it is oscillating at 60 Hz. This also explains why the hot spot jumps from one side to the other. When the wires reverse polarity due to the alternating current, the hot spot switches sides.

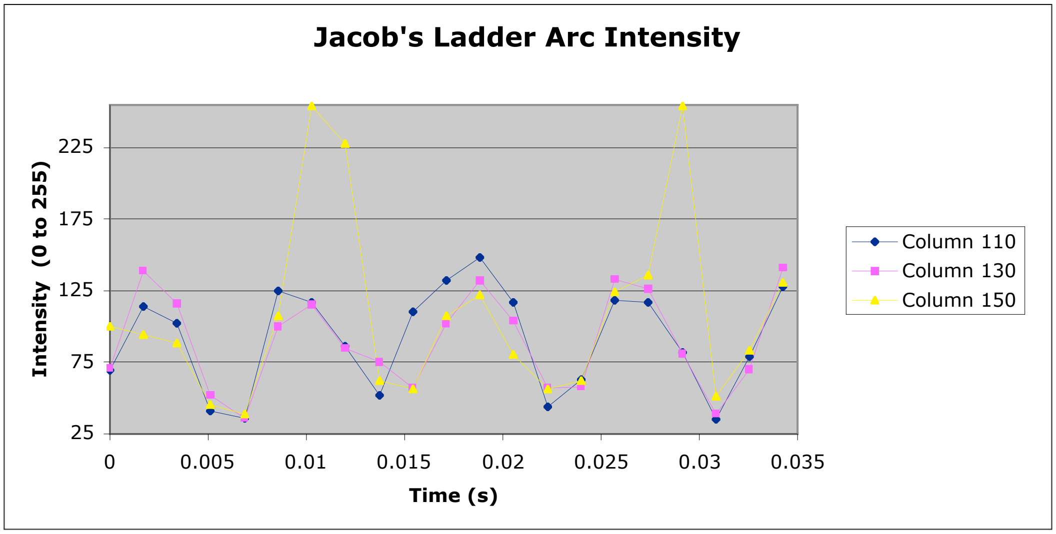

Figure 11. Arc Intensity vs. Time

Viewing the movie frame by frame we notice that we could not find a frame where the arc disappeared. Figure 11. shows intensity values along various x columns over time. Here one can see the oscillatory motion (60 Hz) of the arc as well as the fact that the intensity does not reach zero. Again, it was obvious that the intensity is changing but there is always a faint trace of plasma remaining. The background section of this paper describes three ways in which arcs form: through short circuit heating, pre-ionization, and high-voltage breakdown. In the case of our Jacob's ladder, the distance between the electrodes where the arc forms is .5 cm and we know that we are operating at 15,000 volts. This condition is appropriate for high voltage breakdown condition of 32kV per centimeter described earlier. However, we are not operating at high enough voltages when our electrode gap distance is greater than .5 cm. Our images clearly show that the arc still rises even as it spans 3 cm. The answer can be found in the clue mentioned earlier, we did not see a point when the plasma was "turned off''. Here we are reminded of the second way for an arc to form, preionization. The gas remains excited as it rises due to convection. Again, this can be seen as the gas is still energized in figure 10. When the AC switches polarity, the hot spot forms at a level that the rising excited gas is located. This hot spot formation site is always higher than it was before on the opposite wire and thus the zigzag motion is formed.

CONCLUSION

While we have not unlocked all of the secrets of the plasma ball and the Jacob's ladder, we do know far more than we did before. A fast camera allows us to see these plasmas on a frame-by-frame basis enabling us to see events such as the zigzagging Jacob's ladder plasma and the branching plasma ball. These phenomena appear to follow the theories for streamer and arc formation for the conditions they exist in. Yet, there is much that could still be studied using a tool such as a fast camera. There are cameras available that have better light intensifiers which would allow us to see events in the plasma that are occurring at even faster rates. One way we could use such a camera is to try and see actual streamer and arc formation as a plasma source is turned on. There is also more that could be done with the images we collected, but hopefully this study will serve as part of a foundation in the further understanding of these beautiful sources of plasma.

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