Temporal and Spatial Correlations in Electron-induced Arcs of Adjacent Dielectric Islands

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ABSTRACT
This study investigates very short duration (<1ms) flashes caused by rapid discharge arcs from isolated charged insulating epoxy “glue dots” to an underlying grounded substrate while under electron bombardment. The possibility that a given arc might stimulate arcs in adjacent “glue dots” was investigated through coincidence correlation analysis, as was the dependence of such correlations with “glue dot” separation. Most arcs were found to be random localized events, which occurred only when built up charge produced an electric field large enough for electrostatic breakdown to occur. However, for 40 keV incident beams, some correlation was observed. It is hypothesised that at higher energies more samples are charged close to the breakdown field at any given time and that a discharge in one “glue dot” might cause a sudden electric field spike in neighbouring “glue dots” which could trigger premature arcing. Such stimulated arc rates might reasonably be expected to scale with electric field intensity. A power law fit to the arc data found a power of -1.06±0.09, consistent with a field falling off inversely with separation distance for charges spreading out across a 2D conducting surface.

1. INTRODUCTION
Dielectric materials exposed to energetic electron fluxes similar to those in space plasma environments can emit light in various forms [1]. It is important to understand these charge and discharge phenomena that occur under space like conditions, because spacecraft charging is the leading environmental cause of spacecraft anomalies [2,3]. Two forms of electron-induced light emission have been commonly encountered, both of which emit light from large surface areas that have been charge by the incident electron flux [4,5]. Continuous emission observed whenever a material is exposed to electron fluxes is termed “glow”, or more properly cathodoluminescence (CL) [4,6]. Intermediate duration light emissions events, which start with a large rapid spike in intensity similar to arcs and are followed by an exponential decay (~10-100 s decay constant) back to the continuous equilibrium CL intensity, have been observed for several polymeric and composite materials [1,5].

This study examined an even more common form of electron-induced light emission, short duration (<1 ms), bright photon emissions termed “arcs”, which are caused by the rapid discharge of charged insulators [7]. These arcs are often, but not always, localized to small regions of the charged surface. In previous studies of spacecraft charging, arcing sometimes occurs in neighbouring samples nearly simultaneously although they are electrically isolated from one another. In this study we investigated the relationship between coincident arcing events of nearby charged samples and sample separation.

2. EXPERIMENTAL METHODS
1. Samples
The samples studied were numerous separate insulators on a large conductive substrate (see Fig. 1). The insulators were 36 separate, electrically-isolated, small (~3 mm diameter), approximately hemispherical bisphenol/amine epoxy “glue dots” (see Fig. 2). These were located around the edges of a large conductive

Figure 1. Sample tested. (a) 41x41 cm conductive plate mounted in the vacuum chamber. (b) Sample under electron beam irradiation showing 36 “glue dots” luminescing around the periphery of the sample substrate.
polymeric/carbon nanocomposite (Black Kapton™) substrate (see Fig. 1) [8]. The substrate was mounted inside a high vacuum chamber, attached to a cooled grounded metal plate.

2. Instrumentation

The data collected for this study were taken at NASA Marshall Space Flight Center, using a high vacuum chamber (<10⁻⁴ Pa). The sample was cooled to ~120 K using liquid nitrogen. The chamber was equipped with a high energy (12-40 keV) electron flood gun to simulate electron fluxes and energies seen in a typical space environment. The glue dots were exposed simultaneously to nearly identical electron fluxes (0.3-5 nA/cm²). Beam uniformity was measured to be ±5%, using a movable faraday cup mounted next to the sample plate; this consistent exposure allowed for better stochastic study of the various types of light emissions.

Light emitted from the samples was monitored using a visible to near IR (400-900 nm.), high sensitivity image-intensified CCD video camera (Xybion, ITT ISG-780-1180) at a frame rate of 30 frames per second. This camera was calibrated using a NIST traceable light source with a known intensity at given wavelengths to determine a calibration factor to convert from pixel values to absolute spectral radiance [4]. For bisphenol/amine epoxy, the best estimates for cathodoluminescence material properties are a spectral radiance per incident power density of (1.98±0.04)·10⁻⁹ [W-cm⁻²-nm⁻¹-sr⁻¹ per µW-cm⁻²], a saturation dose rate of 420 µW-cm⁻² (± 30%), and a saturation/de-saturation time constant of 120±40 s [4].

3. Data Acquisition

In order to analyse the data, some video frames with a light on the samples were needed in order to define locations for each sample [see Fig. 2(b)]. A series of dark video frames were also acquired immediately prior to turning the electron beam on, in order to get a good baseline for background subtraction to remove noise and stray light contamination from ambient lights and the electron gun filament glow.

The samples were exposed to the electron fluxes for about 15 min at each energy, with a 2 min break in between each energy. While these light emission data were being acquired, current from the large conductive plate was simultaneously monitored; the plate current was used as a secondary standard after having been calibrated against Faraday cup measurements of the absolute incident current density.

3. DATA ANALYSIS

1. Video Processing

To analyse the data, the video files were converted to individual .jpg images, and then run through a custom Matlab program which was designed for this study. This program allowed for various regions of the substrate images with different shapes to be identified by the user for each beam exposure. For each individual video frame, the pixel values for all pixels in each region summed, divided by the number of pixels, and multiplied by a calibration factor for the video camera to determine the average absolute spectral radiance emitted from that region in each frame. Analysis of regions for each glue dot and several background regions of sequential frames after correction for stray light contamination, created an array of calibrated intensities (absolute spectral radiance) versus time for each region. These data, along with the electron flux data, were then stored for later analysis. Fig. 3 shows a typical curve of absolute spectral radiance versus exposure time for a single “glue dot”.

2. Arcing Analysis

An algorithm was developed to determine if an arc occurred in each frame of the luminescence data. A few methods were tested to determine a current threshold in
curves of absolute spectral radiance versus exposure time for a single “glue dot” (e.g., Fig. 3); any data point with intensity above the threshold is deemed an arc. The arc threshold is set as:

(i) the average spectral radiance plus 1σ, 2σ, 3σ, 4σ, or 5σ (See Fig. 3).
(ii) the average spectral radiance plus a similar factor time the range of spectral radiance calculated as the average minus the minimum intensity.
(iii) the upper bound (first zero to the right of peak) of a histogram of the spectral radiance data (see Fig. 4).

The various methods used to determine the intensity threshold to define arcs produced similar results. An average arc rate of 1-3 arcs per min were observed, with the rate exhibiting a small exponential decrease with increasing incident energy [4]. Upon inspection of the video frames to manually look for arcs it became evident that arcs vary greatly in intensity as well as spatial extent. This most likely caused many arcs to be lost in the noise and it may account for the asymmetry of the intensity distributions we observed. In the end, the best method for counting arcs was found to be creation of a histogram of the intensities and to define the threshold as the upper bound of the distribution.

3. Correlation Analysis

A temporally correlated arc was defined to be an arc that occurred within ±1 frame (±33 ms) of an arc in a separate sample. To test for spatial correlation between arcs in nearby samples the following definition was used. The total number of correlated arcs in sample j caused by arcs in sample i, \( N_{i,j} \), was divided by the total number of arcs in sample i, \( N_{total(i)} \) to determine a correlation value between samples \( i \) and \( j \) for the element \( C_{i,j} \):

\[
C_{i,j} = \frac{N_{i,j}}{N_{total(i)}}.
\]  

This produced a two dimensional correlation matrix with values ranging from 0 (no correlation between the samples) to 1 (perfect correlation). Figure 5 shows two examples of this analysis. Green areas show correlation between groups of samples. White stripes are pixels that had no arcing at this energy. The diagonal elements are perfect self-correlations.

To improve the contrast of the non-diagonal elements of the correlation matrix, their values were normalized to show how each element related to the average, \( C_{avg} \), and standard deviation, \( \sigma_C \), of the correlation matrix:

\[
C_{i,j}^{norm} = \frac{(C_{i,j} - C_{avg})}{\sigma_C}.
\]  

Thus, a normalized correlation matrix value of 8 indicates a coincidence rate between sample pairs 8 standard deviations above the average (presumably uncorrelated) correlation rate. Fig. 6 shows the normalized correlation matrices for the two examples shown in Fig. 5.

4. RESULTS

The possibility that a given arc might stimulate arcs in adjacent “glue dots” was investigated through coincidence correlation analysis. The dependence of such correlations with “glue dot” separation was also studied. The correlation matrix analyses described above were done for incident electron energies between 12 and 40 keV and for fluxes between 0.71 and 5.82 nA-cm\(^{-2}\).
Analyses of the 25 keV data shown in Figs. 5(a) and 6(a), and similarly data from other lower energy data sets, show very little structure; that is, little to no correlation was observed. We conclude that for lower incident electron energies most arcs are found to be random events which occur as localized phenomena when built up charge produces an electric field large enough for electrostatic breakdown to occur.

By contrast, for large incident energies regions with good correlation were seen for groups of nearby samples. Figs. 5(b) and 6(b) are examples of such behaviour for 40 keV incident beams.

The correlation of coincidence events versus the distance between samples was also tested. To determine how the correlation values scaled with sample separation, this distance was computed for each sample pair with the Pythagorean theorem using the pixel values of the center of each region. The correlation values were graphed versus sample separation as shown in Fig. 7.

Again, little or no correlation was found for lower incident energy data [e.g., Fig. 7(a)]. However, a clear trend was found for some higher incident energy data sets such as for the 40 keV data shown in Fig. 7(b). A power law fit to these data found an inverse relation between the correlation and the separation distance, with a power of $-1.06 \pm 0.09$.

5. CONCLUSION

The results of this study found little to no correlation was observed for lower incident electron energies; most electron-induced arcs were found to be random events which occur as localized phenomena when built up charge produces an electric field large enough for electrostatic breakdown to occur. However, for higher incident energies (and consequently, higher power and dose rates), correlation of arcing between some regions was observed. The coincidence rates of these correlated regions also exhibited a trend with separation distance; closer regions tended to be more correlated.

One possible explanation for the lack of correlated arcing at lower incident electron energies may be the need for the samples to be charged close to their individual breakdown potentials in order for one discharge to trigger other discharges. It appears that coincident arcs are most likely to happen when the incident electron dose rate is large enough to ensure that most of the samples are charged close to their respective breakdown limits at any given time; this was only seen with incident energies of 40 keV in this study. It may be that for lower energies there was not enough charge in the samples to have a triggered discharge.

A discharge in one “glue dot” may cause a sudden spike in the electric field of neighbouring “glue dots” which could trigger premature arcing. Such stimulated arc rates
might reasonably be expected to scale with electric field intensity. If confined to a 2D surface (i.e., discharged current spreading out on the conductive plate), the field—and hence the correlation rate—would fall off inversely with separation distance. The power law fit to the arc data found for some higher energy data sets is consistent with this $1/r$ power drop off model.

This study was an afterthought of the original study for which the data were collected. As such, there were many deficiencies in experimental design which could be accounted for in future investigations. The “glue dots” were not regular shapes and had a modest range of exposed surface areas and volumes; better design would employ more uniform insulator regions. The “glue dots” had numerous bubbles in them and asperities, which most likely produced higher fields and a higher arc rate. Because the “glue dots” were positioned around the periphery of the conductive sample, there was not a good sampling of all possible distances. A much better experimental design would employ a square grid of epoxy samples, with one or more uniform separation distance(s). It would be better to do this study with a cooled camera to improve the signal-to-noise ratio as much as possible. A more effective way to block stray light from the electron gun filament would be beneficial. Lastly, better electrometer data would allow for better determination of arcs by looking for simultaneous footprints in optical and electric measurements. It would also be better to isolate the current coming from individual epoxy dots so that better information about charge dissipation for each dot could be acquired (potentially allowing us to see arcs in electrometer data). Alternately, surface voltage measurements for each dot could provide similar information.

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6. REFERENCES