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Characteristics of the discharge of a charged dielectric in low-pressure air

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ABSTRACT

A charged dielectric generates a series of discharges in the surrounding air when the pressure is steadily reduced from near atmospheric to fractions of a torr. The dielectrics here employed were Mylar and Teflon. With positive polarity different discharge regimes were observed as the pressure varied: spark and long streamers at relatively high pressure; diffuse cloud-like discharges below 266 Pa (2 torr). With negative polarity it is difficult to induce a discharge, due to the absence of an electron-emitting surface. Similarities between our results and some of the features of mesospheric and stratospheric discharges are discussed.

1. Introduction

Electrical discharges produced by a charged dielectric in the air around it have been investigated by a small number of research groups [1–4]. Most of the experiments reported were made at atmospheric pressure and thanks to them it was discovered that the discharge propagates along the interface air-dielectric, i. e. they are surface discharges and for that reason they are known as sliding discharges. It was also found that they can be steered by ancillary electrodes, if needed. Bach and co-workers devised an experimental set up that included a corona electrode whose role was both to charge the dielectric and to trigger the discharge [5]. This research, also made at atmospheric pressure, reports among other interesting facts that the amount of charge transferred by the discharge has a magnitude of the order of 1 nC.

Another instance of investigation of dielectric discharging in low-pressure air is to be found in the characterization of the properties of electrets. As these are dielectrics with a substantial amount of charge embedded in them, the researchers were interested to find what effects a change of ambient pressure would have on an electret. Indeed, it was found that a pressure reduction clearly causes loss of charge. This phenomenon was attributed to a number of reasons among them: spark breakdown and ion desorption [6].

The electric field's threshold for air breakdown under variable pressure p and gap distance d is given by Paschen law that can be stated in the following form [7]:

$$E = \frac{365}{1.179 + \ln(pd)} \quad (1)$$

where the field E is in V/cm, p in torr and d in cm. Note that this formula is valid for parallel, metallic electrodes having a profile that makes the field uniform throughout the inter-electrode volume. It would be logical to expect that Paschen law should also apply to the breakdown of other parallel gaps under variable pressure but, as will be shown below, this might not be always the case.

The effect of a reduced air pressure on breakdown is very important in avionics where the electronic circuits have to operate in a rarified atmosphere in which the discharge onset field is markedly reduced. For example, Brockschmidt reports that the critical field for DC corona inception can vary from 7.2 kV/cm at an 18.3 km height to 4.6 kV/cm at 30.5 km elevation [8]. Also, it has been hypothesised that rovers and manned craft landing on Mars and Earth's moon could acquire electrostatic charge from UV photoionization – plus dust storms in the case of Mars [9]. Clearly, the operational ambient pressure and dielectric charging are

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factors that ought to be incorporated into the design of the insulation of a craft's electronics.

Besides its obvious relevance to electrostatic phenomena, the discharge of a dielectric in low-pressure air can be helpful to understand better the mesospheric and stratospheric discharges associated to a lightning stroke. Transient luminous events (TLEs) are discharge events observed in the upper atmosphere, often in coincidence with a cloud-to-ground impact [10]. Two of the most relevant TLEs are the sprites and the blue jets. The sprites are very long diffuse discharges extending from altitudes 50–90 km that have a characteristic red hue and for that reason they are often termed red sprites [11,12]. It has been postulated that the sprites are large streamers initiated by a quasi-static field changes induced by the sudden removal of large amounts of positive charge in the upper part of a cloud. The removal creates a strong local field where there was none and this initiates avalanches that eventually develop into large streamers [13].

The blue jets are a faster type of discharge emerging above thunderclouds and can appear either in connection with a ground directed impact or on their own and are observed at altitudes 20–40 km [11,14]. It has been postulated that the blue jets are similar in nature to leaders, although they do not necessarily share the properties of a stepped leader [15].

Atmospheric discharges can be modelled in the lab using Marx generators and suitable electrodes. However in our experience the use of metallic electrodes in the lab has some problems: first of all, and, the most obvious, that there are no electrodes in nature; the second one is that at low pressures the discharge has a tendency to go towards the vessel's wall rather than towards the opposite electrode. Plus, when modelling low-pressure discharges it is desirable to have a discharge that is not directly coupled to an HV source as the properties of the source can determine the characteristics of the discharge created. The use of a charged dielectric might be a practical means of decoupling the discharge from the source.

The aim of the present work is to investigate the properties of the discharge produced by a charged dielectric under variable pressure air. The different discharge regimes as a function of the pressure will be analysed. In particular, one of the novel aspects of the discharge investigated here is related to the penetrating, large-scale structures observed at low pressure. Finally, some similarities of the discharge with upper-atmosphere phenomena will also be discussed.

2. Materials and methods

All the experiments were made inside a large cylindrical vacuum vessel, 1.2-m diameter, ~2 m^3 capacity, shown schematically in Fig. 1 with its most relevant components. The ground electrode inside the chamber consisted of a metallic disc which in some of the tests had at its center an electric-field mill (*M* in the figure). The field mill is a rotary device whose vanes are alternatively exposed/blocked in order to generate a signal proportional to the applied field. Here it was used to measure the static electric field produced by the charge on the dielectric. This meter was used only during quiescent periods, i. e. in-between discharges. A near-field, broadband mast antenna (12 cm long) was placed at the bottom of the chamber whose task was to detect electric fields emitted by the discharge on the lower side of the chamber.

As shown in Fig. 1, a dielectric disc was suspended below the ground plane, parallel to it. The gap distance between the two planes was 3 cm. Two different materials were employed in the experiments: Mylar, 0.34 mm thick and Teflon 1.58 mm thick. A corona triode placed below the dielectric was used to electrostatically charge it. Charging was made at the relatively high pressure of 53.2 kPa (400 torr) in order to avoid premature breakdown. The sheet was charged for several hours, depending on the amount of initial charge desired. The corona wires were operated at a DC voltage of ±35 kV. The initial charge density in the experiments varied from 0.6 to 1.2 $\mu C/m^2$, with 0.9 $\mu C/m^2$ being a typical initial value. In all the experiments industrial-grade extra dry air was employed.

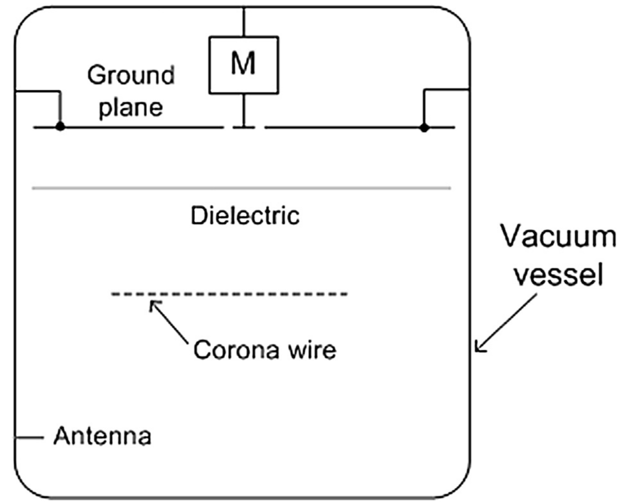

Fig. 1. Schematics of the experimental set-up. *M* is the field mill.

A photomultiplier tube (PMT) installed at one of the viewports was used to monitor the light pulses produced by the discharge and in this way obtain information on the duration and the brightness of the discharge. Another role played by the PMT was to trigger the fast camera when this was employed. During the experiments conventional (Nikon D90) and fast, intensified (Andor iStar 334) photographic cameras were employed to visualize the discharge through two of the viewports of the vacuum vessel. The focal lengths of the lenses employed were 28 and 55 mm (micro).

3. Results

3.1. Charge loss

Once the dielectric sheet was fully charged, the pressure in the vacuum chamber was steadily reduced with the vacuum pump. For positive polarity when the pressure descended below 26.6 kPa (200 torr) electrical discharges began to appear between the dielectric sheet and the plane. When the pressure descended below 13.3 kPa (100 torr), the discharges became more frequent. They were self-triggered and typically 10–20 of them were detected in each run. Every event gradually discharged the dielectric until eventually at very low pressures, ~1.3 Pa (0.01 torr), it got completely depleted. Fig. 2 shows the charge density remaining on the dielectric as a function of air pressure in five tests made using a Mylar sheet as the dielectric.

For the sake of comparison, a plot (solid line) of the amount of charge required to achieve breakdown according to Paschen law is also included in Fig. 2. The conversion from electric field intensity *E* to charge density σ was done through the relationship $\sigma = \varepsilon_0 E$. It is evident from the results in the figure that the threshold calculated from Paschen law is nearly one order of magnitude higher than the measured values.

The curves in Fig. 2 follow a power law. An empirical fit to the remaining charge density σ on the Mylar is given by: