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Low pressure experimental simulation of electrical discharges above and inside a cloud

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Abstract—A low pressure laboratory experiment to generate sporadic electrical discharges in either a particulate dielectric or air, representing a competing path of preferred electrical breakdown, was investigated. At high pressures, discharges occurred inside the dielectric particulate; at low pressures, discharges occurred outside the dielectric particulate; at a transition pressure regime, which depends on conductivity of the dielectric particulate, discharges were simultaneously generated in both particulate dielectric and air. Unique use of a particulate dielectric was critical for sporadic discharges at lower pressures which were not identical in character to discharges without the particulate dielectric. Application of these experimental results to the field of atmospheric electricity and simulation of the above-cloud type discharges that have recently been documented, called jets and sprites, are discussed. Published by Elsevier Science Ltd

INTRODUCTION

C. T. R. Wilson postulated that electrical discharges could occur between thundercloud tops and ionosphere (Wilson, 1956, 1925). Visual observations from earth of these above-cloud (AC) discharges are rare. However, recent National Aeronautics and Space Administration (NASA) Space Shuttle missions (Boeck *et al.*, 1995; Vaughan *et al.*, 1992) and airborne/ground-based experiments (Sentman *et al.*, 1995; Wescott *et al.*, 1995; Sentman and Wescott, 1994, 1993; Lyons, 1994; Franz *et al.*, 1990) have observed and documented AC electrical discharges. Different types of AC discharges were: 'jets' that appear to squirt from thundercloud top as bright blue flashes fanning upwards to altitudes of ~30 to 40 km (Fig. 1a, courtesy of Sentman and Wescott, 1994); and 'sprites' that are diffuse, erect streamers, with bright tops extending to altitudes of ~60 to 90 km (Fig. 1b, courtesy of Lyons, 1994). Several plausible mechanisms for sprite formation have been theorized (Rowland *et al.*, 1995; Taranenko *et al.*, 1993; Pasco *et al.*, 1995; Rycroft, 1994); however, no suitable theoretical explanation for jets has been formulated.

To further help understand the occurrence of AC discharges, a laboratory experiment was designed with crystalline particulate dielectric-air media to simulate these two types of electrical discharges above thunderclouds. It is not possible to replicate completely all complex atmospheric conditions in the laboratory that influence AC discharges; however, some very critical parameters can be investigated, e.g. breakdown electric E-field, pressure, effective charge separation, and simulated thundercloud electrical conductive properties. Thus this controlled experimental simulation is an attempt to recreate similar electrical discharges within or from a charged cell, like theoretical computer models with their assumed input parameters. This paper presents a basic physics experiment of electrical breakdown in the presence of particulate dielectric-air media with appropriate electrode separation. The discharges generated here have some similar characteristics to that observed in the atmosphere and may provide insight into complex phenomena of AC discharges. More details of this experiment are given in Jarzembski and Srivastava, 1995.

EXPERIMENT AND OBSERVATIONS

Figure 2 shows a schematic of the experimental simulation. This set-up represents a particulate dielectric media with dipole structure under an isopotential conducting surface. A chamber with vacuum pump and air flow connections was used such that pressure, p, could be stabilized. Inside the chamber, pulverized salt crystals (particle dia. ~20 μm), a particle ensemble acting like a leaky dielectric, were placed. Inside the salt several wires, pointing upward, were inserted from the bottom with tips below (~ 5 mm) the salt top level. They acted as positively charged anodes of the circuit. A thin insulating tubing was slipped over the bottom half of the wires partially to shield positive charges leaking from the bottom. Below the anode on the side at a distance of ~ 1 cm from the anode wire tips, wires were placed that were negatively charged cathodes of the circuit. At a distance of ~5 cm above the salt level, two different cases of a conducting medium were investigated: (i) horizontal metallic plate and (ii) vertical metallic wires. The relative potential of the conducting mediums above the salt and the cathode wires in the salt were thus lower than the anode. This presented two competing paths of ionization, providing possible simultaneous discharges inside or outside the charged cell of salt crystals. Thus, pressure changes in this experiment provide the preferred path of electrical breakdown in either particulate dielectric or air above it, which-ever first reaches the breakdown threshold E-field (Jarzembski and Srivastava, 1995). A Glassman, Series EH, DC high voltage power supply (0–60 kV, 0–1.5 mA) was used to create large E-fields between the electrodes.

(*i*) *Short diffuse discharge with horizontal metallic plate*

For this set-up with a smooth isopotential conducting medium above the charged cell, sporadic electrical discharges were observed occurring only within salt for p ranging from ~700 to ~300 mb at an average of E_c ~1000 to ~600 kV/m, respectively (Fig. 3a). E-fields caused motion of salt crystals, occasionally accelerating them toward the upper metallic plate, confirming that the salt top was being positively charged. With a decrease in p, air conductivity above the salt increased, resulting in lowering of the E-field for air breakdown threshold. Therefore, decreasing p increased the influence of the upper metallic plate on creating discharges in air above the salt top; consequently, E-fields required lower threshold levels for random discharges. Weaker E-fields subdued movement of salt particles.

Figure 3(a–c) shows photographs of discharges within the salt and also those emanating from the salt towards the metallic plate. At p between 300 and 150 mb, discharges occurred within the salt (Fig. 3a); however, small bluish discharges ~5–15 mm long emanated from the salt top surface. Figure 3(b) shows discharges above the salt top with the same magnification as Fig. 3(a). They were sporadic and usually oriented at different angles but did not visibly reach the metallic plate. Depending on discharge intensity within the salt, discharges above the salt top were sometimes narrow or wide. These occurred after intense discharges within the salt had already taken place, emanating from tiny transient depressions or holes (~ 1 mm deep) created by strong E-field activity near the salt surface even though the anode wire tips were not exposed. These tiny holes, generated at the salt top, seemingly created preferred regions from which those above salt discharges propagated upwards. Sometimes more than one of these discharges occurred simultaneously on the salt surface. These discharges were brighter near the salt top, fading to a faint bluish spray at the discharge top. Lowering p between ~150 to 20 mb, the discharges became more erect and intense bluish white (Fig. 3c), requiring lower E-fields. The intense white portion of the discharge visually stopped part way to the metallic plate with a very faint blue diffuse plasma at its top. Depending on p and the threshold breakdown E-field, the visible length of these discharges varied, though did not visibly reach the metallic plate. The E-fields, E_j, required for generation of discharges above the salt top varied from ~200 to 50 kV/m for p ~300 to ~20 mb, respectively. This is what we refer to as 'jet-type' simulation since the experimental observations show these discharges emanating from the top boundary of a charged cell as also observed above a thundercloud (Fig. 1a).

(*ii*) *Streamer discharge with vertical metallic wires*

In the previous set-up, no filament streamer-type discharge occurred with a smooth isopotential metallic plate until a slight indentation/irregularity in the plate was created from which a rare streamer discharge was observed. Thus, for set-up (ii), the metallic plate was modified by suspending a vertical metallic wire (negatively charged) from the plate at the chamber top (Fig. 2). Slightly lower p and E-fields were required for this experiment because plasma initiation was facilitated from a wire as this allowed channeling of electron flow above the salt top. Figures 3(d to i) show photographs of the discharges for this case. Sequentially, first a bluish-white discharge was observed at the salt top and along with this electrical activity at the salt top, an occasional bright point glow discharge was observed at the end of the conducting wire (Fig. 3d). This discharge at the salt top viewed from above (Fig. 3e) sometimes had a fluctuating highly-branched radial discharge within the salt. The E-fields, E_{sl}, required for generation of the branched discharge at the salt top varied from ~100 to 50 kV/m at p ~70 to 20 mb. As E-fields were slightly increased with increased current, this branched discharge fluctuated or disappeared momentarily, resulting in rapid

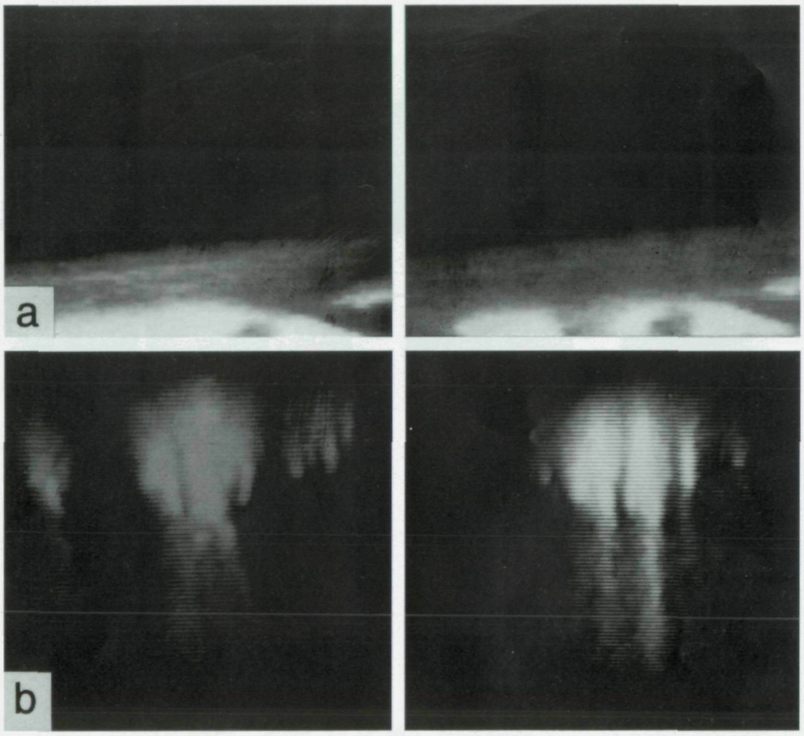
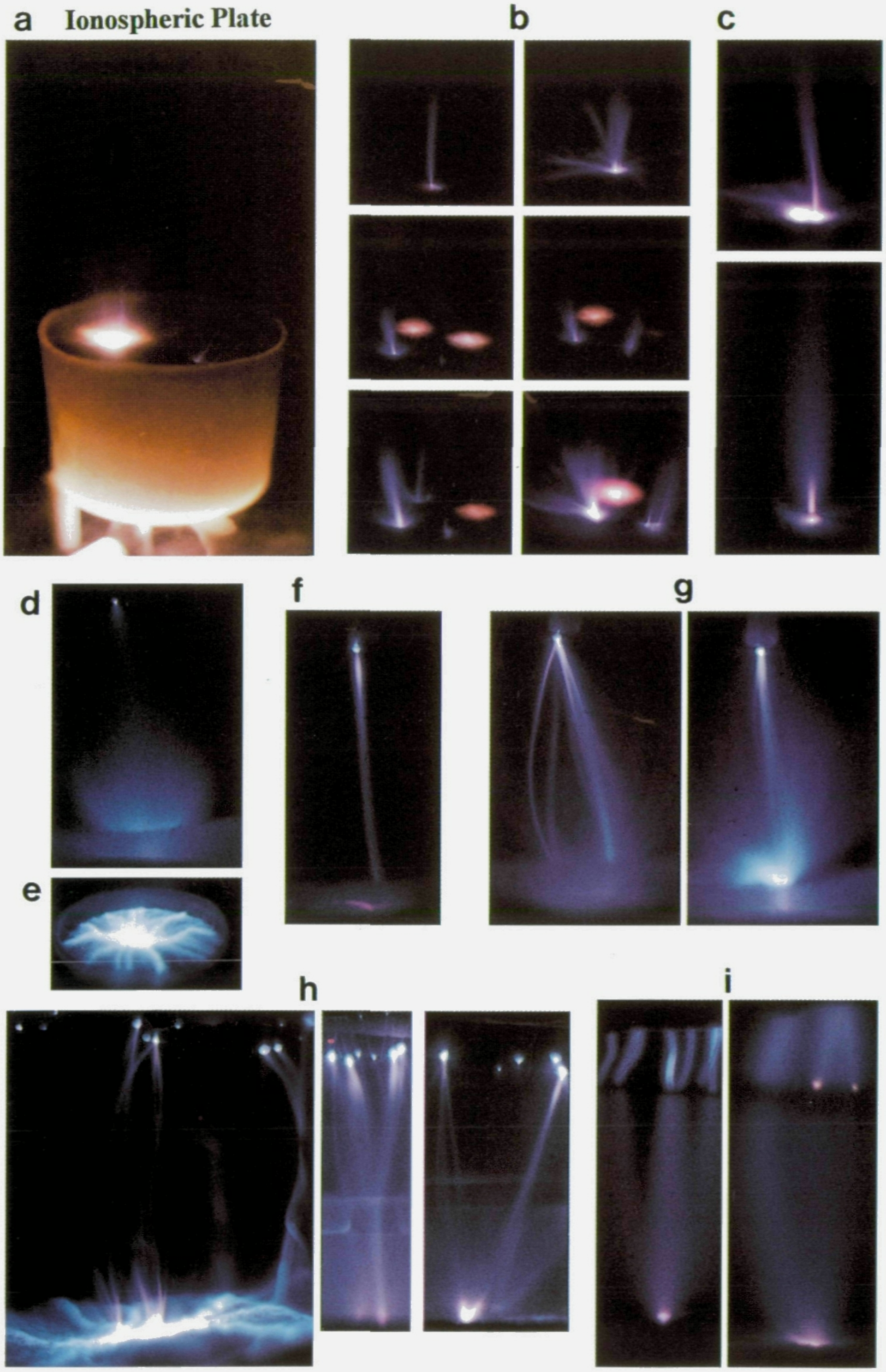


Fig. 1. Photographs of above-cloud (AC) discharges: (a) jets (courtesy of D. D. Sentman and E. M. Wescott, 1994); and (b) sprites (courtesy of W. A. Lyons, 1994).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Ionospheric Plate
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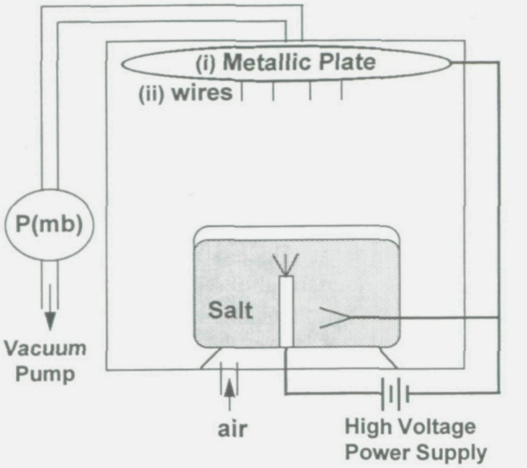

Fig. 2. Experimental schematic for generation of discharges inside or outside a particulate dielectric for either case (i) horizontal metallic plate or case (ii) suspended vertical wires.

E-field variations. This caused an intense nearly white tenuous, streamer discharge below the bright point glow discharge at the wire tip (with a faint 'pop' sound) meeting part way a more tenuous rising, bluish discharge from the salt top (Fig. 3f). Fluctuations of the salt top discharge caused faint streamers; however, its momentary disappearance caused brighter streamers. Fluctuation or disappearance of the branched discharge and appearance of the streamer occurred in rapid succession. Also, from the same occasional wire point glow discharge, more than one of these diffuse streamers was observed, not always following the same track (Fig. 3g). Multiple wires were also suspended from the metallic plate. Here, many sporadic wire point glows were observed at $p \sim 100$ mb (Fig. 3h), though not all wires glowed, occurring subsequent to a fluctuating salt top branched discharge. From some wire point glows, streamers appeared which faintly connected with the bright salt top, some at the branched discharge center, and some along its branches. The flat metallic plate did not give a streamer except when some rough point on the plate (with concentration of electrons) would glow with an occasional streamer, subsequent to the fluctuating salt top discharge. Thus when small wires were suspended from the upper plate, it was possible to produce consistent streamer discharges.

As p was lowered to ~ 1 mb (minimum achievable in this chamber), the entire suspended conducting wire length gave a long sporadic, diffuse glow discharge (instead of a point glow discharge) with a darkened region just below followed by a diffuse discharge above the salt top (Fig. 3i). The narrow horizontal dark region observed in Fig. 3(i) is the 'Faraday dark space' of neutralization that occurs near a glowing cathode which is well documented for low pressure gaseous electrical discharges (Loeb, 1939). The E-fields, E_s, required for generation of these discharges above the salt top varied from $E_{sl} \sim 100$ kV/m at $p \sim 100$ mb to $E_{su} \sim 10$ kV/m at $p \sim 1$ mb.

DISCUSSION OF DISCHARGE EXPERIMENT

This type of an experiment can be directly applied to the field of atmospheric electricity and interpretation of these experimental results to intracloud (IC) and above-cloud (AC) electrical discharges are presented. In this experiment, the salt crystals simulate the leaky dielectric aspect of a cold ice cloud top, inhibiting continuous flow of charges to the ionosphere. The anode and cathode electrodes in the salt simulate the electric dipole structure of a thundercloud, while the upper metallic plate simulates the upper atmospheric highly conducting medium at altitudes greater than 60 km. The purpose of the vertical wires suspended from the horizontal metallic plate is to suggest possible occurrence of irregularities in the upper atmosphere's electron conductivity which may in part be due to the thunderstorm itself; regardless of how the irregularity of the isopotential surface is produced, our experimental simulation shows that it is required for any streamer-type discharge. The use

Fig. 3. Photographs of discharges (a–c) under a horizontal metallic plate and discharges (d–i) under a metallic plate with suspended vertical wires, shown in Fig. 2. For the horizontal metallic plate: (a) $p \sim 300$ mb, discharges within salt along with faint bluish upward discharges at salt surface, (b) $p \sim 300$ to 100 mb, various narrow upward discharges as seen emanating from salt top but not visibly reaching the ionospheric plate, (c) $p < 70$ mb, discharges with spread out, blue, diffuse tops. For the suspended vertical wires: (d) $p \sim 150$ to 100 mb, bluish-white discharge at salt top with wire point glow discharge, (e) bright salt top viewed from above occasionally has a radial-branched discharge in salt top layer, (f) $p \sim 100$ mb, single streamer discharge from the wire point glow and connecting faintly with salt top discharge, (g) $p \sim 100$ to 50 mb, more than one diffuse streamer discharge from a single wire point glow, (h) $p \sim 100$ to 50 mb, more than one wire point discharge, with several streamers, and (i) $p \sim 1$ mb, more diffuse elongated glow along the wires, the 'Faraday dark space', and fainter bluish discharge connecting to salt top. (The faint horizontal demarcation seen in some pictures is due to light scattering from the partial shielding tubing).

of the DC power supply is only to provide simulation of potential difference in the already established thundercloud dipole structure just prior to the discharge; how the charge got separated or what drives the currents in thunderclouds is not part of this simulation.

Ice cloud simulation by salt crystals

The uniqueness of this experiment is the inclusion of salt crystals in a low pressure chamber. Salt was used because its crystalline particulate dielectric properties, ionic structure, and electrical activity allow it to hold charge much like that in a cloud of ice particles. Conductivity of pure bulk salt (NaCl) is similar to that of distilled water (O'Dwyer, 1964). When bulk water breaks up into droplets and crystallizes into ice crystals at lower temperatures and when bulk salt is pulverized into salt crystals, both their conductivity decreases while the capacity to hold charge increases. In this experiment, conductivity of salt crystals lies in the same range as that of cold electrified cloud tops (Caranti and Illingworth, 1983; Smyth and Hitchcock, 1932; von Hippel, 1954; Pruppacher and Klett, 1978; Griffiths *et al.*, 1974). Thus the low conductivity of salt crystals enables the charged cell in this simulation efficiently to hold and shield charge, which is an important characteristic of thunderclouds. As a result, salt facilitated a realistic simultaneous simulation of IC and AC electrical discharges occurring in E-field ranges similar to that observed in real storms. Since conductivity of substances covers an enormous range, some particulate dielectrics gave a response similar to salt (Jarzembski and Srivastava, 1995), though depending on conductivity different chamber pressures and threshold E-field were required for discharges. Finally, big salt crystals (particle dia. $\sim 400\ \mu m$) inhibited formation of above the cell discharges, creating discharges only within the cell as the conductivity of large particulate dielectric is higher than that for the smaller pulverized crystals.

Also, the salt layer thickness above the anode had a significant impact on the occurrence of these discharges by providing a shielding/screening layer. If the anode was slightly exposed, a continuous discharge was observed, equivalent to a discharge between two electrodes with the only medium being air. If the overlying salt layer was too thick, no discharges above the salt top occurred. If salt was removed, discharges only occurred in air between the anode and cathode closest to each other, and did not at all occur toward the ~ 5 times more distant metallic plate either with or without suspended wires. Without salt, discharges did not resemble those in Fig. 3 and did not replicate features of those above real storms.

The discharges

For case (i), the discharges above the salt top observed in this simulation exhibited two slightly different kinds of appearance for a range of p. At $p \sim 300$ to 150 mb (p at cloud top altitudes) first they were narrow and then became more diffuse at lower p up to ~ 20 mb (p at middle stratosphere altitudes). They resemble the natural observations of jets (Wescott *et al.*, 1995; Sentman and Wescott, 1994). As the experiment indicates lower p increases air conductivity, making discharges more diffuse and spread out (repulsion of like charges) with charges having longer mean free paths and tending to follow lines of E-field toward the ionosphere, accounting for the fanning, diffuse, structure of the jets. These would fan out at lower pressures above until complete neutralization.

For case (ii), the discharges above the salt top show resemblance to a sprite discharge. Figure 3(f–h) shows a diffuse tenuous streamer discharge from a single extremely bright wire point glow discharge which is remarkably like the filamentary discharge below a single bright mesospheric sprite top discharge (Fig. 1b). However, the extremely low mesospheric pressure (~ 0.1 mb at 65 km) would cause the discharge to be more diffuse, as Fig. 3(i) shows. As the experiment indicates, atmospheric sprites can be considered as a combination of discharges in different pressure regimes: at lower $p < 1$ mb of mesospheric pressures, the elongated bright red glow at sprite top (simulated by the bright wire length glow discharge) connecting with a diffuse streamer discharge in a slightly darkened region, 'Faraday dark space'; and at higher $p \sim 150$ to 100 mb near cloud top boundary, the bluish-white radiation initiated from occurrences of intense possibly branched intracloud lightning in the bright cloud top. Sprites cover ~ 4 orders of magnitude in p in the atmosphere; therefore, since the mesospheric region is at $p < 0.1$ mb with higher conductivity (lower pressure and higher conductivity than that achieved in this experimental simulation), it is possible that the mesospheric response in creating the conductive column and red glow occurs at even lower E-fields < 10 kV/m at $p \sim 1$ mb achieved in this simulation, and probably before the stratospheric tenuous blue discharge, which may or may not occur (Sentman and Wescott, 1994).

CONCLUSIONS

From the experimental simulation of IC and AC discharges, some plausible criteria for the formation of jets and sprites may be hypothesized. Figure 4 shows

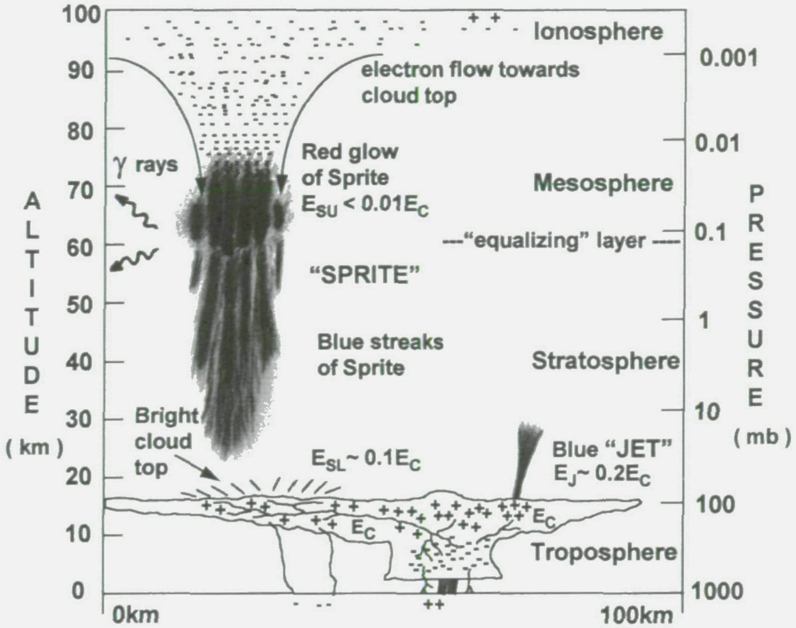

Fig. 4. Schematic of jets and sprites, summarizing some fundamental characteristics of both types of discharges inferred from observations and simulation.

a summarized schematic of these AC discharges. AC discharges occur most easily when there is intense space charge regions built up very near the cloud top, producing IC discharges within the charged cell.

For jets, the upper thundercloud positive charge centers reside close to the physical cloud top boundary. If they are buried too deep within the cloud, leakage above the cloud may be inhibited; hence, build-up of charge would occur primarily within the cloud resulting in only IC lightning. Moreover, if they are residing at the very cloud top, a continuous flow of charges to and from the ionosphere with little or no charge build up would occur, inhibiting AC discharges. Preferred regions in the cloud top boundary may be created under the combined influence of IC discharges near the cloud top, mesospheric/ionospheric electrons, and cloud dynamics, allowing positive charge to leak out in a squirt.

Sprites visibly extend to altitudes 60 to 90 km, which implies intense electrical activity in both thundercloud top and upper atmosphere. As observed both in the atmosphere (Sentman *et al.*, 1995; Sentman and Wescott, 1994) and in the simulation, sprites appear to be associated with an intermittent intense bright discharge at the cloud top layer, causing the observed blue and white bright cloud top (Sentman and Wescott, 1994) which seems to be a precursor to sprites. Further, the E-field simulated in laboratory conditions by a conducting wire represents channeling and concentration of moving mesospheric/ionospheric electrons. Thus, the hypothesis made here, from the outcome of the simulation, is that for the generation of long, diffuse, filamentary streamer-type discharge some perturbation of the upper conducting medium is required. This implies a lowering of the upper atmosphere isopotential surface towards the electrically active cloud top which would occur in response to sudden changes in E-field due to a major discharge observed as the bright bluish-white cloud top (Sentman *et al.*, 1995; Sentman and Wescott, 1994) before the onset of the sprite. Thus, the motions of mesospheric/ionospheric electrons are considerably modified, producing transient, elongated, relatively more conducting, columnar regions in the mesosphere of high density electrons as they are accelerated toward the bright electrically active cloud top. The upper sprite bright red glow (occurring between 50 to 90 km) is probably due to this intensification of rapid free electron motion in a conducting column as well as similar sporadic long wire glow in the low pressure simulation. Mesospheric discharges and bright cloud top lightning occur together but may or may not visually connect, as observed both in this simulation and atmosphere (Sentman and Wescott, 1994). As seen in Fig. 3h, some wires gave a glow discharge but did not visibly connect with the cell top. Occasionally the sprite streamers do not visually connect with the bright cloud top due to electrons not having enough kinetic energy to ionize this region of higher p (~ 50–10 mb corresponding to altitudes of ~ 20–35 km) above the cloud.

In charge transfer within a streamer, electrons descending from the upper conducting medium meet the rising positive charges. This would, unquestionably, cause a slightly neutralized darkened region, the 'Faraday dark space', between the negative glow and positive column of a low-pressure gaseous discharge (Fig. 3f–i). This is also observed in most atmospheric sprites as a slightly darkened space between the bright upper red columnar glow and the fainter bluish streamers in the stratospheric region (Fig. 1b). It is a more diffuse and less distinct analog of the neutralization region because the sprite discharge in the mesosphere is not bounded as in a metallic lab-cathode. However, this dark space, diffuse but undoubtably present in most sprites, further confirms a realistic simulation achieved in this experiment and also suggests that possibly both polarities of charge are in motion.

The upper sprite glow may be located in the mesospheric 'equalizing' layer at altitudes of 60–70 km where enhanced E-fields have been already found to exist (Reid, 1986). This would assist in focusing electron motion from the upper mesosphere and lower ionosphere in response to E-field changes in the cloud top, causing intense heat and shock waves which may be the characteristic 'popping' sound heard in sprite occurrence (Sentman and Wescott, 1994). Estimates of altitudes of the upper columnar glow of sprites may provide evidence of the 'equalizing' layer altitude.

The rapid movement of electrons in the 'thundercloud-modified mesosphere' could be analogous to a linear accelerator tens of kilometers long where the electron flow is being concentrated in the elongated upper bright glowing column of the sprite. In the simulation for $p \sim 1$ mb, the glow along the wire, analogous to the upper sprite glow, occurred at $E_{su} \sim 10$ kV/m. Since, in this first simulation, it was not possible to achieve the low pressures and high conductivity due to the unbounded electrons in the mesosphere, one can only extrapolate E-fields. So, at lower mesospheric $p \sim 0.1$ mb, only $E_{su} \sim 1$ kV/m or less may be needed for a discharge. In addition to this, the higher conductivity due to the presence of moving free electrons would further lower the E-field, $E_{su} < 1$ kV/m, required for sprite onset in the 'thundercloud-modified mesosphere'. These conditions in the elongated (~ 10 km) upper sprite glow would provide sufficient E-fields for electron acceleration to kinetic energies ($\sim$MeV) capable of producing gamma radiation (Fishman *et al.*, 1994) through collisions with atmospheric ions.

This experiment, with the unique use of a crystalline dielectric, allows a realistic simulation of simultaneous AC and IC discharges. Further, it offers a comparison with features of some theoretical mechanisms on sprite formation. One of the mechanisms suggests that an upward propagating electromagnetic pulse from cloud lightning can interact with the upper atmosphere (Rowland *et al.*, 1995; Taranenko *et al.*, 1993). This would cause perturbations in the electron density and acceleration of free electrons, leading to a discharge. Another theory considers that intense quasi-electrostatic fields, resulting from large charge distributions that transiently exist in and above thunderclouds, possibly cause local heating of the upper atmospheric electrons to breakdown intensities (Pasco *et al.*, 1995). Further, Rycroft (1994) has based a theory on whistlers, which precipitate energetic free electrons in the upper atmosphere. This may enhance the local electrical conductivity and effectively lower the ionospheric equipotential surface in the vicinity of high E-fields present above thunderclouds, causing further acceleration and a cascade of free electrons, leading to a discharge between the thundercloud and ionosphere. Also, it has been suggested that cosmic ray activity may play a role. Further, Velinov and Tonev (1995) have shown that an electrified cloud can provide localized E-fields in the upper atmosphere which may help in initiating sprite formation. Conditions such as high transient charge distributions near the cloud top boundary, rapid E-field variations due to IC discharges, and localized perturbations in the medium above the charged cell were also required for this experimental simulation.

There are very little atmospheric data in the vicinity of AC discharges to characterize them fully, e.g. in-cloud and above-cloud conductivity, upper atmospheric E-field variations, mesospheric/ionospheric structure above thunderstorms, cloud charge location, and cloud dynamics. This experimental work provides further insight into some of these parameters. In addition, this technique can allow future laboratory measurements of current flow, charge transfer, spectroscopy with inclusion of stratospheric-type gases and ions, possibly variable radioactive sources for conductivity changes, and other atmospheric parameters which would help in modeling, parameterization, and prediction of these events.

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