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Low-Pressure Electrical Discharge Experiment to Simulate High-Altitude Lightning Above Thunderclouds

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Low-Pressure Electrical Discharge Experiment to Simulate High-Altitude Lightning Above Thunderclouds

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I. INTRODUCTION

Lightning is a very complex phenomenon that has been studied intensely for many years. Yet, in spite of many observations, new aspects of lightning are still being discovered. Lord Kelvin's (1860) interpretation of the global electric circuit treated the Earth system as a leaky spherical capacitor in which Earth and the upper atmosphere were good conductors and Earth's atmosphere served as a leaky dielectric where electrical discharges both within thunderclouds and cloud-to-ground occur. Later, C.T.R. Wilson (1920) proposed that these thunderclouds are actually electrical generators separating electric charges within this spherical capacitor. He further postulated[1] in 1925 that electrical discharges could also be expected to occur from thundercloud tops toward the ionosphere.

From Earth, visual observations of these high-altitude discharges between cloud and ionosphere are rare. However, recent NASA space shuttle missions viewing Earth's atmosphere, while conducting the mesoscale lightning experiment using low-light level television cameras located in the shuttle payload bay, have videotaped these events.[2–4] Further, recent airborne and ground-based experiments dedicated to observe high-altitude lightning discharges from very active thunderstorms have also documented these spectacular events.[5–15] Different types of high-altitude discharges observed were "jets" that start as bright blue flashes, which appear to squirt from the thundercloud top and fan upwards, reaching altitudes of ~30 to 40 km; and others called "sprites" that are erect but diffuse, with bright tops that extend up to altitudes of ~60 to 90 km. Observations of jets are very recent.[5 6] Figure 1 shows photographs of (a) jet discharges, courtesy of D.D. Sentman and E.M. Wescott;[5] and (b) sprite discharges, courtesy of W.A. Lyons,[8] above electrically active thunderstorms. The roles of the electrical and dynamical characteristics of thunderclouds, upper troposphere, stratosphere, mesosphere, and ionosphere for formation of these high-altitude cloud-ionosphere discharges are not presently well understood.

There is very little atmospheric data documented concerning these high-altitude cloud-ionosphere electrical discharges and most of the information is visual. In an attempt to understand the formation and occurrence of these discharges, a controlled laboratory experiment was designed to attempt to produce electrical discharges from a simulated thundercloud. It is not possible to completely replicate all complex atmospheric conditions in the laboratory; however, some critical parameters can be addressed that influence these discharges. This experiment allows investigation of pressure, breakdown E-field strength, electrode configuration, and dielectric properties of the simulated thundercloud that trigger discharges toward the ionospheric medium. The discharges generated here have some similar characteristics to those observed in the atmosphere. This simulation experiment may provide some insight into complex phenomena of high-altitude cloud-ionosphere lightning.

a

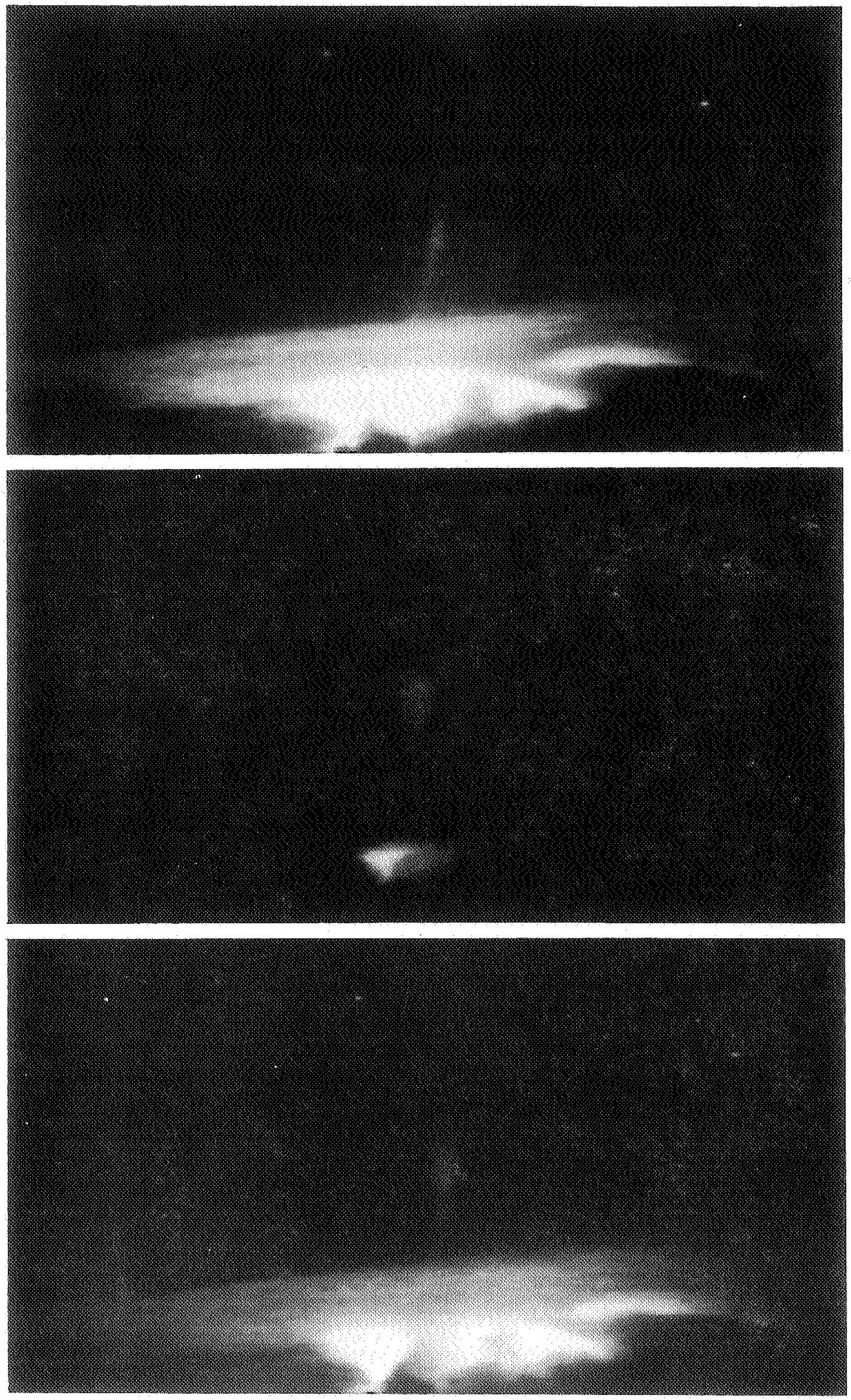

Figure 1. Black and white photographs of high-altitude jets (a) (courtesy of D.D. Sentman and E.M. Wescott[5]) and sprites (b) (courtesy of W.A. Lyons[8]). Other pictures of sprites can be seen in references 2 to 5 and 7 to 15. Features of jets are faint, bluish color, narrow in the beginning and fanning out at the top, reaching altitudes of 30 to 40 km, while sprites have bright red elongated tops with a less bright blue tenuous streamer-like plasma below and a bluish-white glow at the thundercloud top.

b

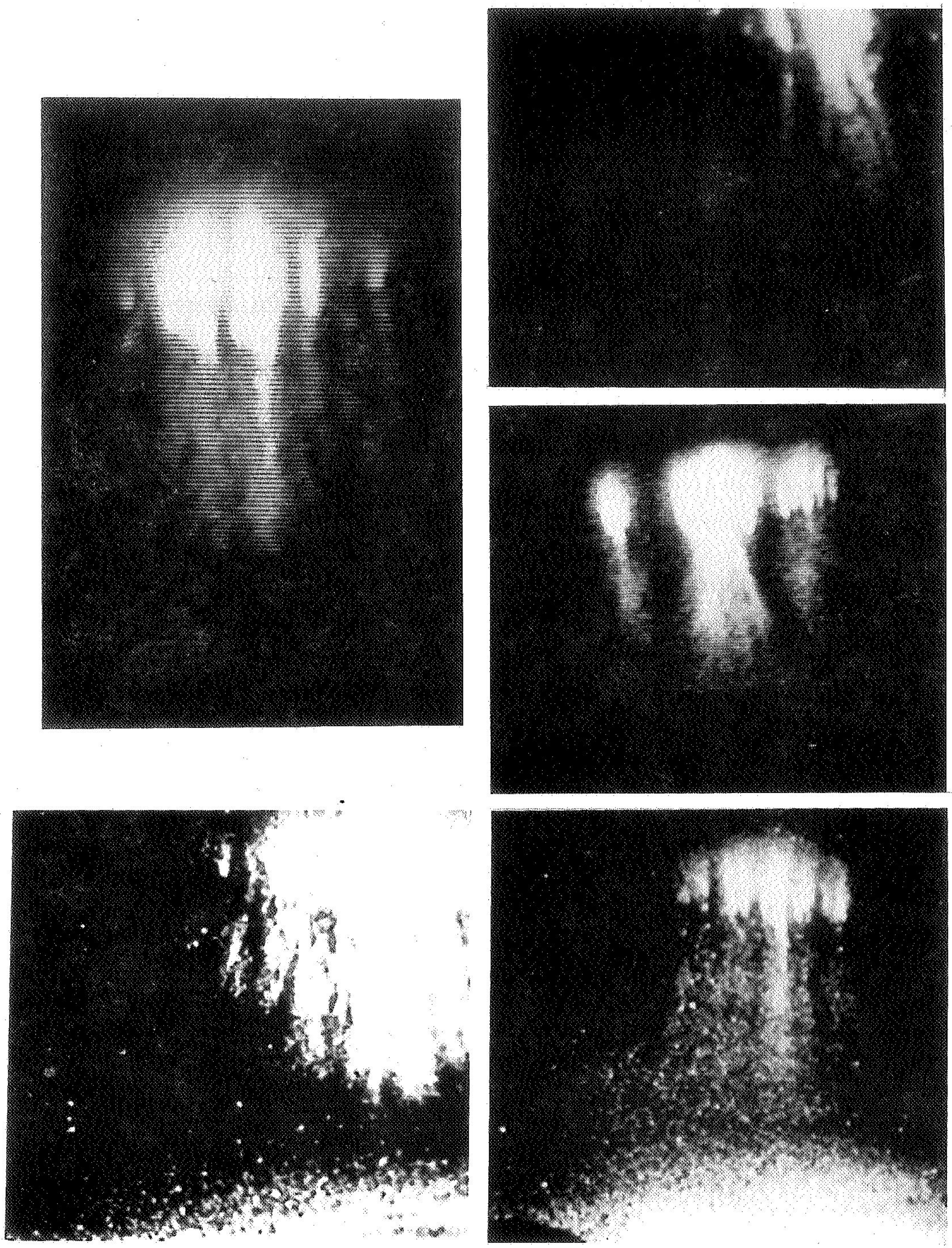

Figure 1.—Continued.

II. EXPERIMENT

Figure 2 shows a schematic of the experimental simulation. A clear plexiglas cylindrical chamber 10 cm in diameter and 10-cm high with insulating top and bottom was used. Through top and bottom port holes, vacuum pump and air flow connections were made. Pressure within the chamber could be lowered to simulate pressure at various atmospheric altitudes. Inside the chamber, a thundercloud was simulated using a cylindrical clear plastic container (3 by 3 cm) containing pulverized salt crystals (particle mean diameter ~20 μm), a material that acts like a leaky dielectric (discussed in more detail later).

A. Discharge With Ionospheric Plate: Visually Analogous to Jets

Inside the salt container (fig. 2), several wires were inserted from the bottom of the container such that the wires were separated and pointing upward. The wire tips (region No. 1) were ~5 mm below the salt top level. They were positively charged to make the anode of the circuit, representing a positive charge that is generally found within a thundercloud top. A thin insulating tubing was slipped over the bottom half of the wires to partially shield positive charges leaking from the bottom (region No. 2). Two more electrically connected wires were placed (region No. 3) below the anode on the side at a distance of ~1 cm from the anode wire tips. These wires were negatively charged to make the cathode of the circuit, representing the lower negative charge of the thundercloud. At a distance of ~5 cm above the salt level was a horizontal metallic plate 7.5 cm in diameter, representing the ionosphere (region No. 4). The relative potential of regions Nos. 3 and 4 are kept

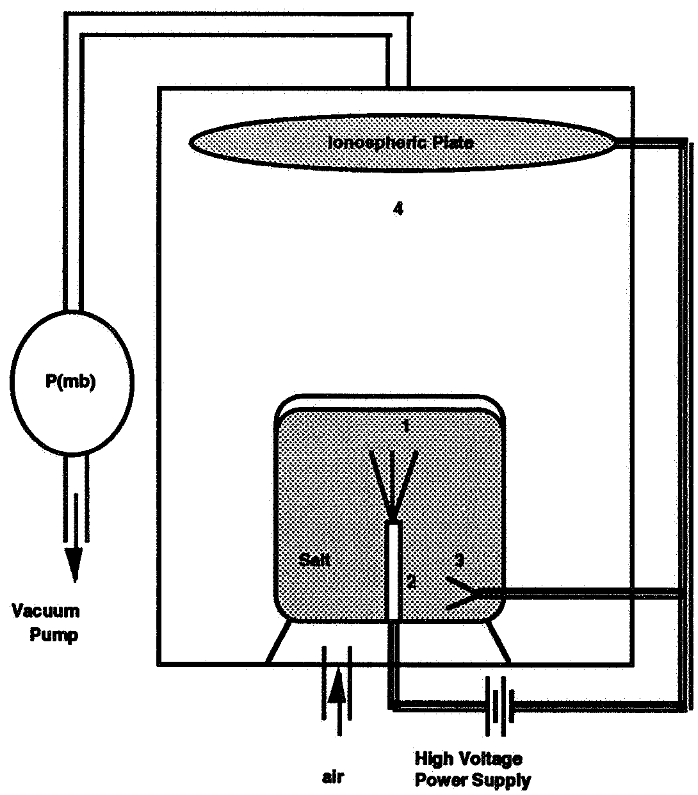

Figure 2. Experimental schematic of a simulated electrified thundercloud below an ionospheric plate to generate jet-type discharges.

lower than the anode (simulating that the upper positive charge of the cloud has higher potential than both the ionosphere and the lower negative charge of the cloud) to present two possible competing paths of ionization, simulating lightning within the thundercloud as well as outside. The aim here was only to study the lower pressure high-altitude discharge and not to completely replicate the potential or the complexity of the lower negative charge that would occur at higher pressures than the thundercloud top positive charge. A Glassman series EH direct-current high-voltage power supply (0 to 60 kV, 0 to 1.5 mA) was used to create large E-fields between the electrodes.

For relatively high pressures, ranging from atmospheric pressure of ~1,000 to ~300 mb, electrical discharges were quite sporadic, occurring only within the salt between regions Nos. 1 to 3 and Nos. 2 to 3 at an average of E_c ~ 1,000 to ~600 kV/m for p ~ 700 to ~300 mb, respectively, and simulating intracloud electrical discharges. The breakdown of salt with respect to air and its relation to cloud is presented in greater detail in the next section. E-fields tended to cause motion of the salt particles and even to accelerate some of them from the salt top toward the ionospheric plate. This was an indication that the salt top was being positively charged as intended. It is well known that with a decrease in pressure the air conductivity increases, resulting in lowering of the E-field intensity for the breakdown threshold of air. Therefore, as pressure was further decreased, the influence of the ionospheric plate on creating electrical discharges in the air above the salt top increased; consequently, E-fields were lowered to the threshold levels of individual discharges. The weaker E-fields subdued the movement of salt particles.

Figure 3(a–c) shows photographs of discharges from the simulated thundercloud top emanating toward the ionospheric plate. At pressures between 300 and 150 mb, electrical discharges still occurred within the salt (fig. 3(a)); however, small bluish discharges ~5 to 15 mm long were seen to emanate from the top surface of the salt near region No. 1. Figure 3(b) shows a series of different discharges above salt top level with the same magnification as figure 3(a). These discharges were sporadic and usually oriented at different angles but did not visibly reach the ionospheric plate. Depending on the intensity of discharges within the salt, the discharges above the salt top were sometimes narrow but occasionally wide, similar to those observed in nature (fig. 1(a)). These occurred after electrical discharges within the salt had already taken place and emanated from tiny transient depressions or holes (~1-mm deep) created by strong E-fields near the salt surface, even though the wire tips of the anode were not exposed. These tiny holes, generated at the salt surface top layer by discharges from regions Nos. 1 to 3 and Nos. 2 to 3, apparently created preferred regions from which these discharges above the salt top propagated upwards. Intense electrical activity within the salt sometimes caused more than one of these discharges to occur simultaneously on the salt surface. These discharges were brighter near the salt top and faded to a faint bluish spray at the discharge top. With a further decrease in pressure of ~150 to 50 mb, the discharge phenomena became more erect and intense bright, bluish white (fig. 3(c)), as compared to previous ones. The intense white portion of the discharge visually stopped part way to the ionospheric plate, with a very faint blue diffuse plasma at its top. Depending on chamber pressure and breakdown E-field strength, the visible length of these discharges varied. At threshold E-field levels, they usually did not reach the ionospheric plate. Also, when the salt crystals were moved by shaking the chamber, the discharges would occur more frequently at the threshold E-fields, suggesting that cloud dynamics could affect these discharges.

These discharges above the salt top layer seem to exhibit two slightly different kinds of appearance. At higher pressure, they were narrow, while at lower pressures, they were more diffuse at the top. The individual discharges observed in this simulation may resemble natural observations of jets[5] except for a fanning out at the top observed in nature. The atmospheric pressure gradient above thundercloud tops, not possible to simulate in a small chamber, may partially account for the a

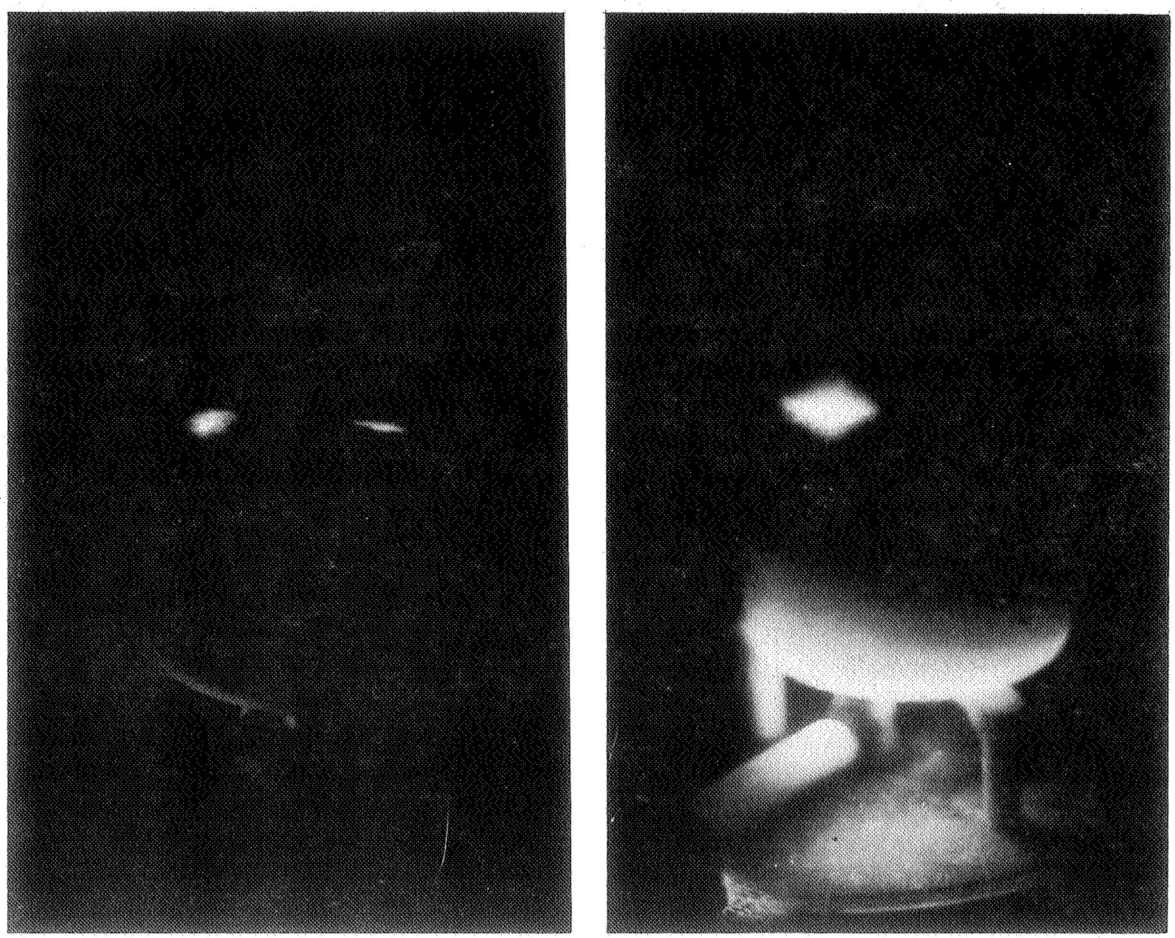

Figure 3. Photographs of discharges (a,b,c) from setup shown in figure 2 for jet simulation. The ionospheric plate is located at approximately the top of each photograph in (a,b,c). (a) $p \sim$ 300 mb, discharges within salt occur along with small faint bluish upward discharges at the salt surface.

b

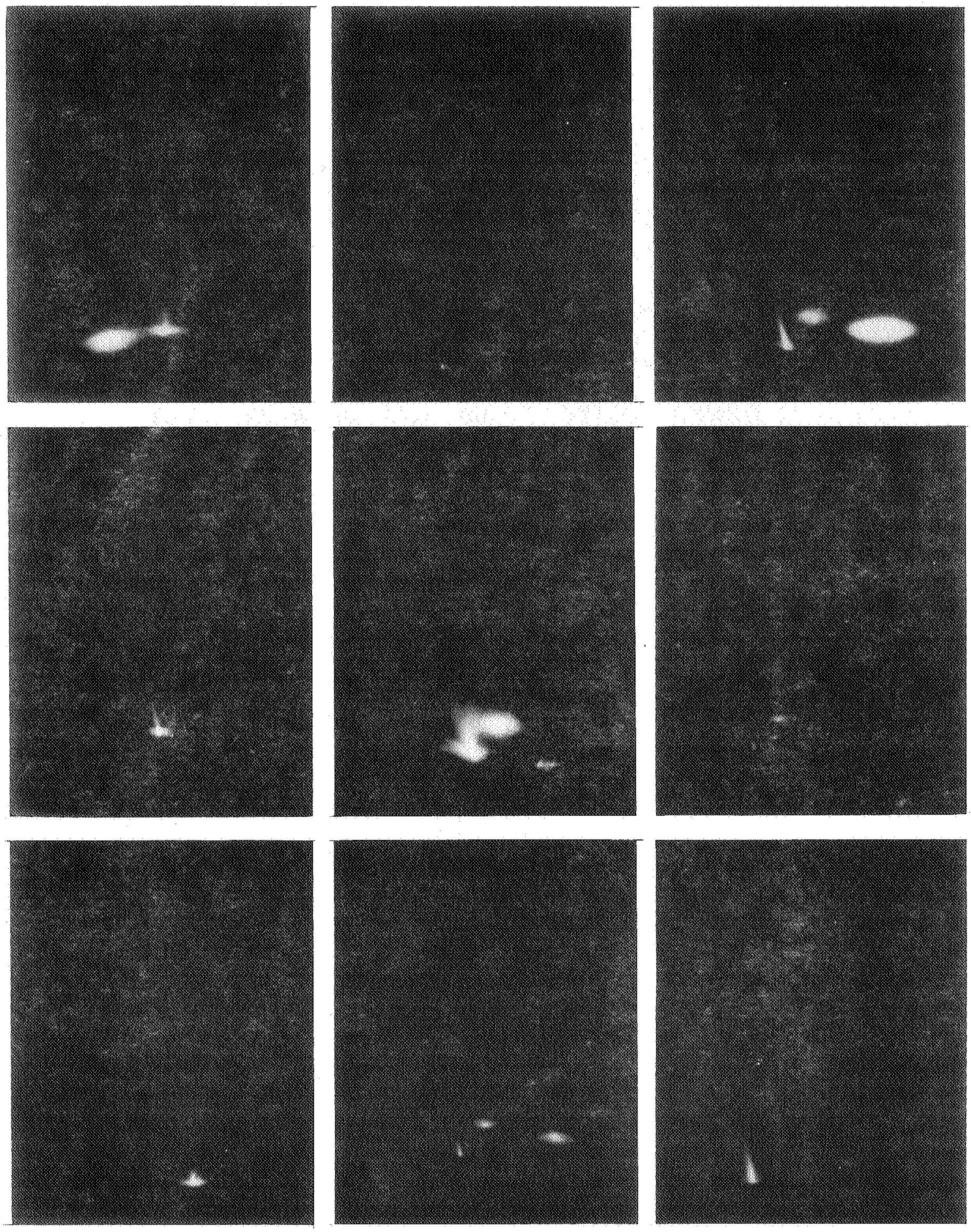

Figure 3. (b) $p \sim 300$ to 100 mb, various kinds of narrow upward discharges as seen emanating from salt top but not visibly reaching the ionospheric plate.

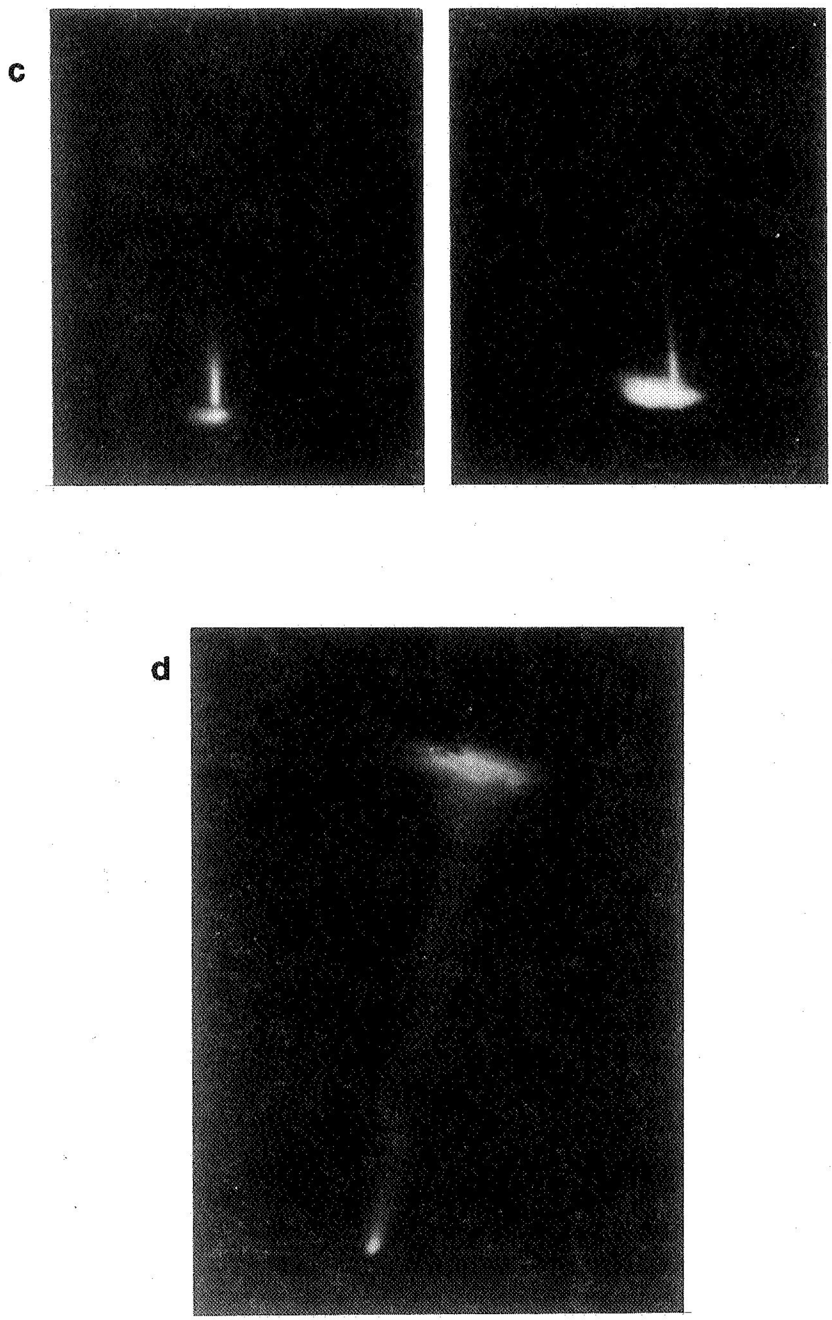

Figure 3. (c) $p < 70$ mb, discharges with spread-out, blue, diffuse tops. The ionospheric plate is located at the very top of each photograph. Discharge for reverse polarity of the electrodes is shown in (d), which does not resemble jet discharge.

fanning or trumpet structure of the jets because as pressure is decreased, air resistivity decreases such that discharges become more diffused and spread out (repulsion of like charges) as charges have longer mean free paths and may tend to follow lines of E-field toward the ionosphere. In the lab, it is difficult to create a two- to three-orders of magnitude pressure difference similar to the one between thundercloud top and the ionosphere and still maintain a stable simulated particulate thundercloud within the chamber. However, the discharges, studied for a range of different chamber pressures, showed that at higher pressures (300 to 150 mb, analogous to pressures at thundercloud top altitudes) first they were narrow and then became more and more diffuse as pressure was decreased (up to ~20 mb, which would refer to conditions in the middle stratosphere) similar to the observed jets. The E-fields, E_j, required for generation of discharges resembling jets above the salt top varied from ~200 to 50 kV/m for $p \sim 300$ to 20 mb, respectively.

In the experimental setup, tests were performed in which the polarity of the electrodes was reversed. This may represent the situation when some negative charge is at the thundercloud top while the ionosphere is positively charged. In this case, discharge mostly emanated from the upper ionospheric plate, with the salt top near the cathode becoming bright, and continuous diffuse faint streamers of plasma followed E-field lines, in the shape of paraboloids, between the ionospheric plate and cathode (fig. 3(d)). This did not resemble jets observed in nature. Hence, the simulation results suggest that the jets probably occur from positive-charge centers near the thundercloud top, with brighter narrow channels occurring at cloud top pressures, fanning out into a more diffuse spray at lower pressures. Jets would probably be associated with small current flow and little mesospheric/ionospheric activity as compared to the sprites described next.

B. Discharge With Ionospheric Wire: Visually Analogous to Sprites

Sprites visibly extend to altitudes as high as 60 to 90 km, reaching the ionospheric region, which may imply intense electrical activity in both the thundercloud top and upper atmosphere. In this case, intense charge is probably transiently localized at the thundercloud top that may be causing the observed blue and white bright cloud top,[5 12 13] which appears to be a precursor to sprites. Thus, the hypothesis made here is that in response to sudden changes in the intense thundercloud top charge and electrical activity occurring in the intracloud lightning close to thundercloud top, motion of mesospheric/ionospheric electrons are considerably modified, producing transient regions of high-density electrons in the mesosphere as they are accelerated toward the bright electrically active thundercloud top. The upper red glow, occurring between 50 to 80 km, associated with sprites is probably due to this intensification of moving electrons in a conducting column created by the rapid motion of electrons. The E-field intensity associated with this channeling and concentration of moving mesospheric/ionospheric electrons may be simulated in laboratory conditions by a conducting wire resulting in a point source. Therefore, for simulation of the sprite, the ionospheric plate was modified by suspending a metallic wire (negatively charged) from the plate at the top of the chamber (fig. 4), representing a concentration of electrons pulled toward the thundercloud top. The positive electrode in the salt was brought closer to the salt top (~2-mm thick salt layer above the anode) such that the electrical activity would occur nearer the salt top to simulate the bright thundercloud top. Further, it was slightly shielded from the surrounding salt particles and the cathode in the salt by an insulating tubing (fig. 4) to help concentrate positive charges and reduce discharges to the salt bottom. Lower pressures 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, simulating the transient mesospheric conducting columns that may be created above the thundercloud top.

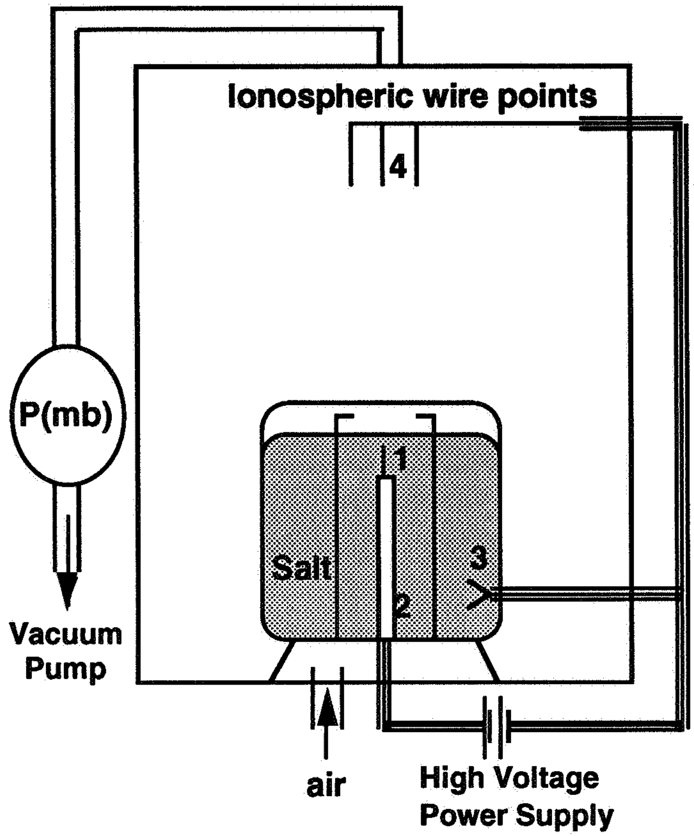

Figure 4. Experimental schematic of simulated electrified thundercloud below an ionospheric wire point source to generate sprite-type discharges.

Figure 5(a to f) shows photographs of discharges for the case of the simulated thundercloud under a wire representing a mesospheric/ionospheric conducting column. Sequentially, first a blue and white discharge occurred at the salt top layer, which appears to be visually analogous to that observed in nature. The blue and white salt top discharge viewed from above (fig. 5(b)) usually had a fluctuating highly-branched radial discharge within the salt. As pressure is decreased, the number of radial branches become less numerous and each branch becomes wider. This branched discharge may partially simulate the dendritic or "spider" lightning near the cloud top in cumulonimbus anvils. This electrical activity at the salt top near the positive-charge center caused a point glow discharge at the end of the conducting wire as shown in figure 5(a). The E-fields, E_{sl}, required for generation of the branched discharge at the salt top varied from ~100 to 50 kV/m and their branched structure only occurred for pressures ranging from $p \sim 120$ to 70 mb. As E-fields were increased very slightly with increased current, the branched discharge in the salt top fluctuated or disappeared momentarily, resulting in E-field variations. This caused a single tenuous, diffuse streamer or streaking discharge, visually resembling a single streamer within a sprite (fig. 5(c)). Fluctuations of the salt top discharge caused faint streamers; whereas, momentary disappearance of the salt top discharge caused brighter streamers. The fluctuation or disappearance of the branched discharge and appearance of the streamer occurred so quickly in succession that it was not possible to capture the two separate events in a timed exposure photograph; however, this event was clearly observed visually and recorded on video. In this case, a bright pinkish-white discharge occurred below the bright wire point glow, representing mesospheric discharge, meeting part way a more tenuous rising, bluish discharge from the salt top. Also, from the same wire point glow, more than one of these diffuse streamers could occur; these may or may not follow the same track, as shown in the two a b c d

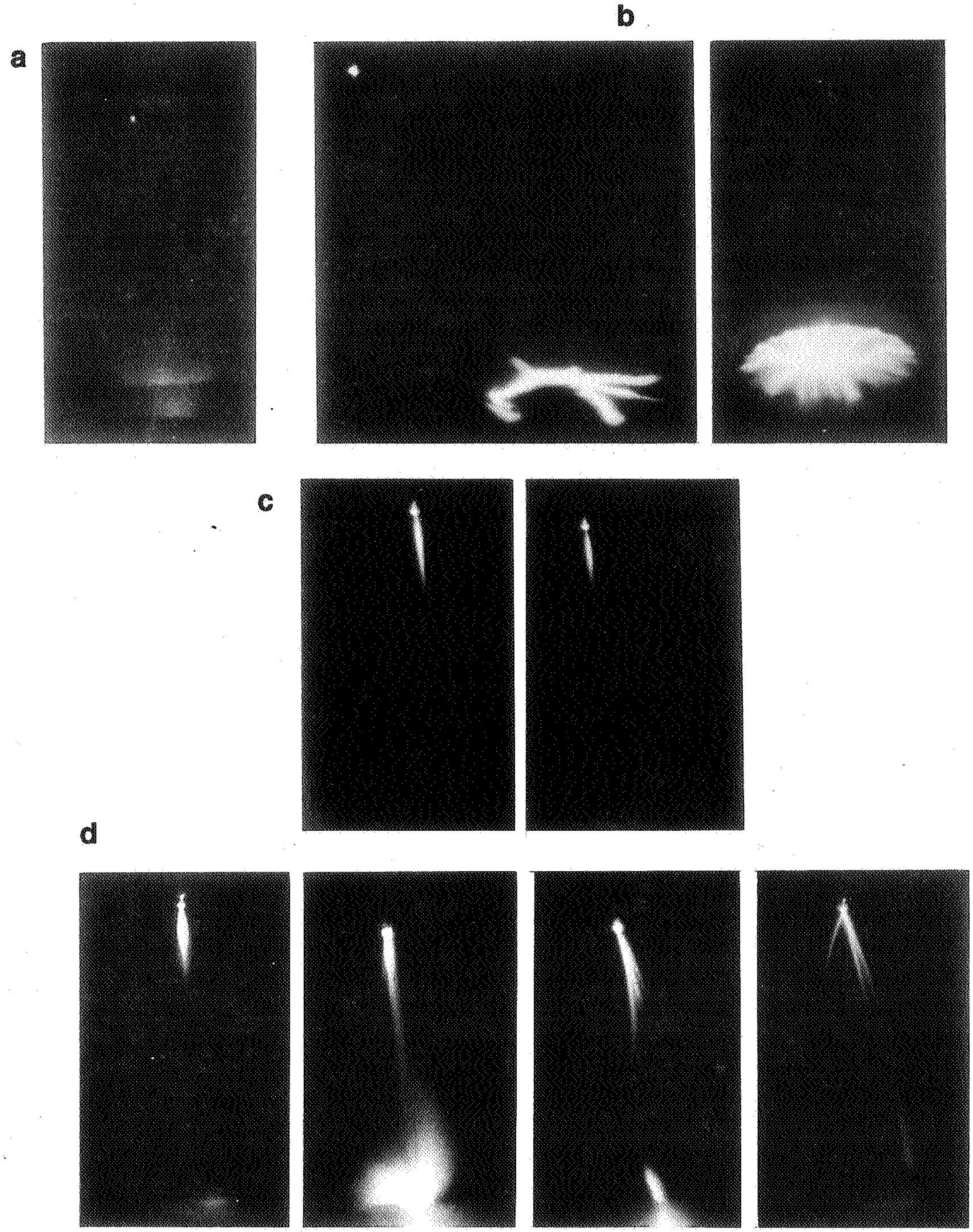

Figure 5. Photographs of discharges (a–f) from setup shown in figure 4 for sprite simulation. (a) $p \sim$ 150 to 100 mb, bluish-white radiation at salt top occurs with induced wire point discharge; (b) bright salt top viewed from above occasionally has a radial-branched discharge in salt top layer; (c) $p \sim$ 100 mb, single-streamer discharge from the wire point glow and connecting faintly with discharge at salt top; (d) $p \sim$ 100 to 50 mb, more than one diffuse-streamer discharge from a single wire glow.

e

f

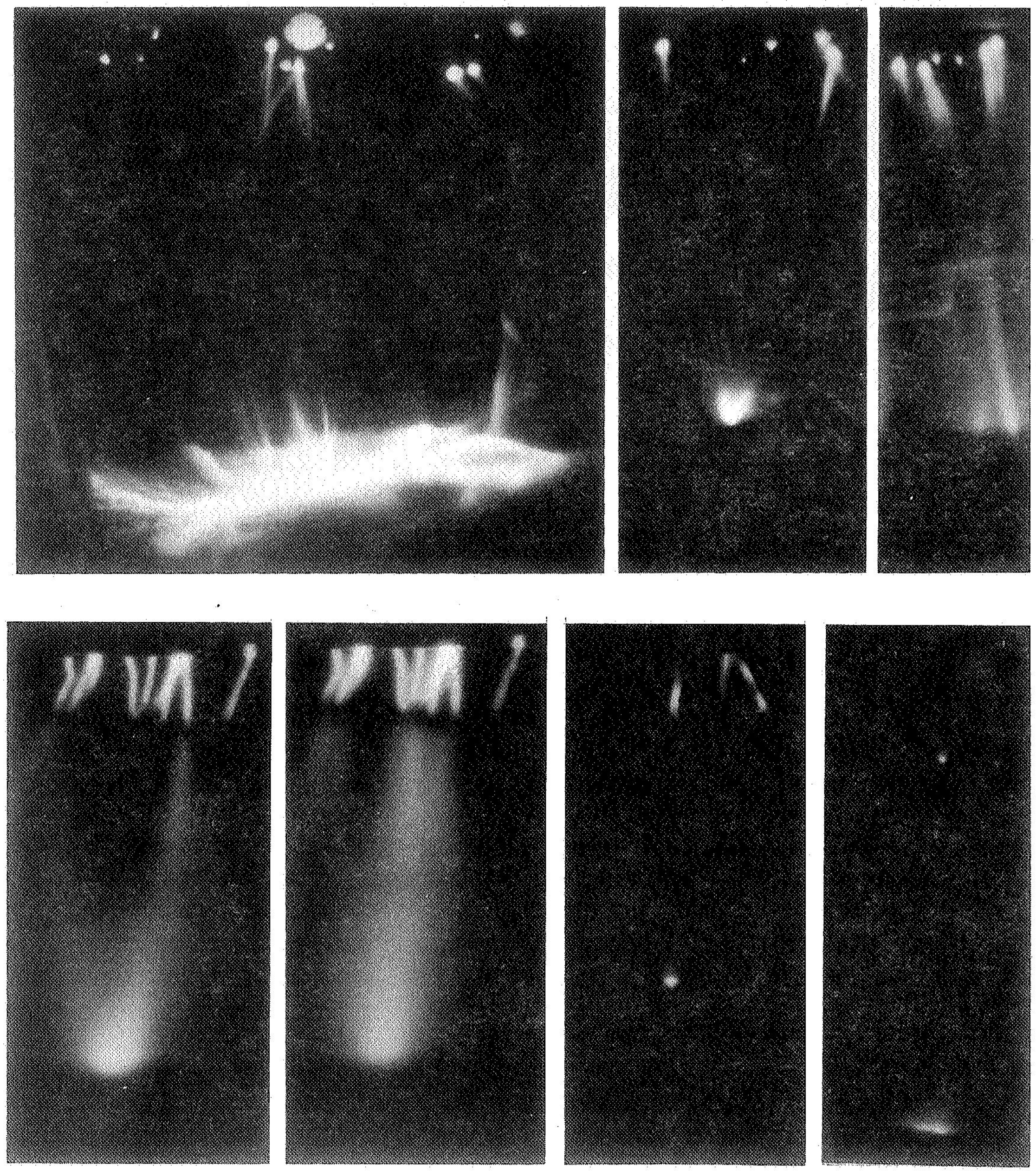

Figure 5. (e) $p \sim 100$ to 50 mb, for more than one wire point discharge with several streamers; and (f) $p \sim 1$ mb intensified and more diffuse elongated flow along the wires, the Faraday dark space, and fainter bluish discharge connecting to salt top. The faint horizontal demarkation seen in some pictures is due to the artifact of light scattering from the partial shielding tubing.

g

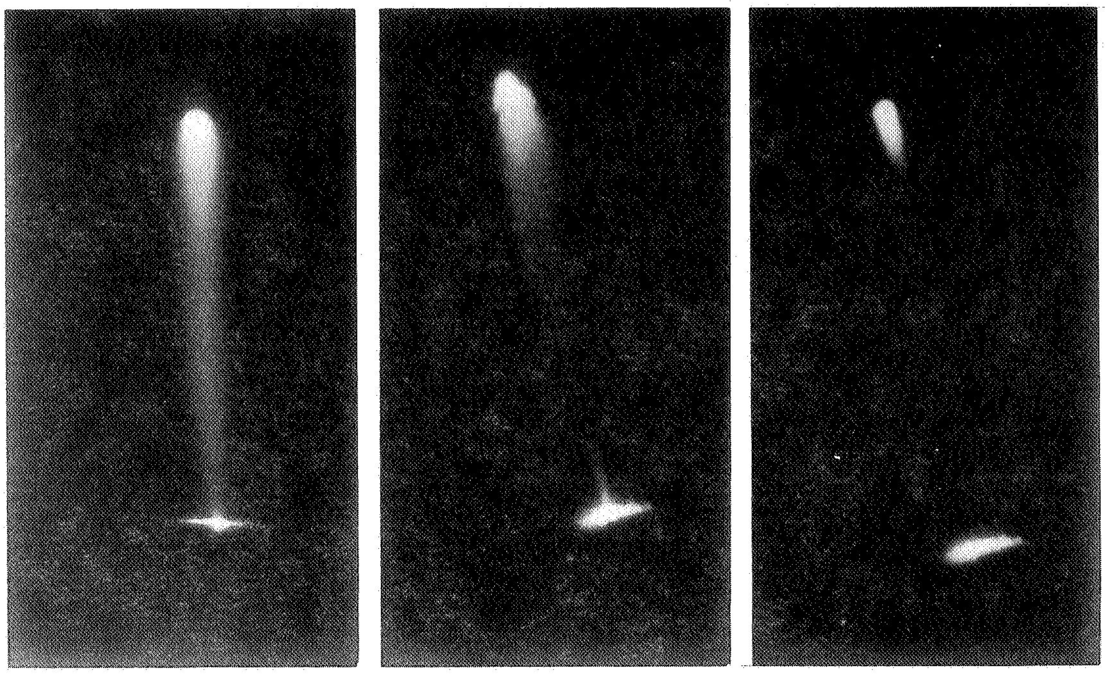

Figure 5. Discharge for reverse polarity of the electrodes is shown in (g), which does not resemble sprite discharge.

photographs in figure 5(d). Figures 5(c and d) simulate diffuse tenuous streamers from a single bright mesospheric discharge at the sprite top as seen in figure 1(b), while the wire point glow discharge, above the streamer discharge, is extremely bright and may resemble the upper part of the sprite top. However, in the atmosphere, extremely low mesospheric pressure (~0.1 mb at 65 km) would cause this point-type discharge to be more diffuse than in the lab simulation. Most sprites observed thus far in nature have occurred in the region of intense cloud-anvil branched lightning and positive cloud-to-ground strokes.[7–9] This implies that the sprite may occur at the positive cloud-top charge center, and the observed bright top that accompanies the sprite may be associated with intense branched cloud anvil lightning occurring near the top.

The fact that many thin striated diffuse streamers have been found to occur within a sprite (fig. 1(b)) suggests that several mesospheric conducting columns of flowing electrons could be created above the bright thundercloud top. To replicate this, multiple wires were placed at the top to simulate the "thundercloud-modified mesosphere." In this case, figure 5(e) shows many wire point glows (not all of the wires glowed) occurring subsequent to a fluctuating branched discharge at salt top. Streamer discharges appeared from some of the wire point glows that faintly connected with the bright salt top region, some at the branched discharge center and some along its branches. The flat ionospheric metallic plate did not give this kind of streamer discharge except when some rough point on the plate would glow from which an occasional streamer discharge emanated, subsequent to the fluctuating salt top branched discharge. Thus, when small wires ~$\frac{1}{2}$ cm in length were suspended from the upper plate, it was possible to produce consistent streamer discharges. Figures 5(c–e) were taken at ~100 mb; the simulated discharge tops are more narrow and well-defined than the tops of the sprites observed in nature, which are more diffuse and spread out due to lower atmospheric pressures. Hence, to study low-pressure effect, chamber pressure was lowered to its minimum of ~1 mb. At this low pressure, figure 5(f) shows conducting wire glows along their entire length with a darkened region just below, which is followed by a very diffuse discharge above the salt top. The elongated, bright-top wire glow in figure 5(f) appears to simulate the elongated red glow of the mesospheric conducting column at sprite top (fig. 1(b)) and may support the hypothesis made here that a concentrated flow of mesospheric/ionospheric electrons may be pulled down toward the thundercloud top, resulting in a very intense upper-level point-type discharge. Since the mesospheric region is at extremely low pressure $p < 0.1$ mb with higher conductivity, it is possible that the mesospheric response in creating the conductive column and red glow occurs at lower E-fields and probably before the stratospheric tenuous blue discharge, which may or may not occur.[5] The narrow horizontal dark region in figure 5(f) is the "Faraday dark space" of neutralization that occurs near a glowing cathode, and has been well documented for electrical discharges in gases at low pressures.[16–18] A more diffuse analog of this neutralization phenomenon may appear in sprites between the bright red top glow and the fainter bluish streamers of plasma in the stratospheric region that follow below it. This dark space, however, is less distinct in sprites because in the mesosphere a more diffused upper sprite discharge is not bounded as in a metallic cathode of the lab experiment. However, this dark space, diffuse but undoubtably present in most sprites, further confirms the realistic simulation in this experiment. Thus, the sprite in the atmosphere can be considered as a combination of discharges in different pressure regimes. At higher pressures (~150 to 100 mb), the bluish-white radiation appears to be rising from the bright thundercloud top from possible occurrences of branched intense intracloud lightning, combined with elongated bright glow at lower mesospheric/ionospheric pressures (simulated by the wire glow) including the slightly darkened region below and some distance of diffuse discharge in the upper stratosphere. 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 (which represents the E-field at lower sprite discharge) to $E_{su} \sim 10$ kV/m at $p \sim 1$ mb, which represents the E-field at upper sprite discharge.

As an additional test, the polarity of various electrodes and wires was reversed. In this simulation, the discharges had the streamer-like appearance of the previous polarity except that the wire point was found to be extremely active, with more energetic (continuous flame-like discharge) and less tenuous downward discharges as shown in figure 5(g). Continuous discharge and air breakdown from this positive wire point could be easily generated. Also, the salt top became bright reddish white near the cathode but without the characteristic blue and white branched discharge associated with the positive-charge salt top. Most of the sprites observed in nature appear to be associated with a bright blue and white cloud top and positive cloud-to-ground lightning, which may imply more likelihood of a sprite from a positive-charged thundercloud top electrical activity and less from a negative-charge center activity.

III. ICE CLOUD SIMULATION BY SALT CRYSTALS

Electrical discharge in a gaseous medium is well understood,[16–18] while the discharge process in the presence of a dielectric, especially a dielectric in particulate form mixed with air, is much more complicated.[19] The uniqueness of this experiment is the inclusion of salt crystals in a low-pressure chamber, which provides a simple means to study discharge leaking from a particulate dielectric to an ionospheric plate for jet simulation or to and from an ionospheric point for sprite simulation. The purpose of this section is to provide some validity for use of the salt crystals which were critical in simulating electrical discharges from cold electrified thundercloud tops.

Salt was used because its crystalline particulate dielectric properties, ionic structure, and electrical activity allow it to hold a charge that may be analogous to a cloud of ice particles. Furthermore, salt crystals simulate the leaky dielectric aspect of a cold ice thundercloud top fairly well by shielding the positive-charge center and inhibiting continuous flow of charges to the ionosphere. This may enable charge buildup in localized regions, resulting in sporadic discharges. Conductivity of pure bulk salt (NaCl) is ~10^{-4} mho m^{-1}, similar to that of distilled water.[19] When bulk water breaks up into droplets and crystallizes into small ice crystals at lower temperatures, its conductivity decreases and its capacity to hold charge increases. Measurements show that ice crystal conductivity decreases to values of ~10^{-8} mho m^{-1} (refs. 20 and 21) and lower while relative permitivity is ranging from ~10 to 3 (refs. 21 and 22) in cold conditions ($T < -50$ °C) for low electromagnetic frequencies, $f \sim$ 100 Hz. Similarly, when bulk salt is pulverized into very small salt crystals, its conductivity decreases while its capacity to hold charge increases. Measured conductivity of salt crystals is ~3.3×10^{-12} mho m^{-1} and relative permitivity is ~5.9 (ref. 22) for low electromagnetic frequencies, $f \sim$ 100 Hz (appendix A). In an electrified cloud where ice crystals are sparsely dispersed in air at colder temperatures and higher altitudes, cloud conductivity is lower than clear air at the same levels,[23 24] as the ice cloud charge capacity is higher. This clear air conductivity above thunderstorms at ~15 km has been measured to be ~4×10^{-12} mho m^{-1} (ref. 25) and strongly electrified cloud conductivity is calculated to be lower, which could range from ~10^{-12} to 10^{-14} mho m^{-1}.[23 24] Thus, in this experiment, conductivity of salt crystals lies in the same range as that of cold electrified cloud tops. Since cloud conductivity is quite variable, depending on cloud electrification, particle size, particle concentration, temperature, and pressure, it is not feasible for this simulation to compare conductivity between thunderclouds and salt crystals to an accuracy finer than an order of magnitude. Thus, the low conductivity of salt crystals enables the simulated thundercloud to efficiently hold a charge, which is an important characteristic of thunderclouds. This causes a bound charge to buildup in this simulation as in thunderclouds containing dispersed ice crystals. As the bound charge on the salt crystals builds up, it becomes highly polarized. Within the salt medium between various electrodes, bound charges are probably localized near the electrodes creating intense charge centers. With increase in *E*-fields beyond saturation of bound charges in the medium between the electrodes, an avalanche of free charges[19] causes discharge to possibly occur in two competing regions: (1) only within the salt at higher pressures, simulating intracloud lightning; or (2) leaking out of the salt at lower pressures, simulating cloud-ionosphere lightning (appendix B). The branched discharges from the positive-charge center observed in the salt top layer resemble the appearance of cloud anvil-type lightning and suggests that our simulations may be realistic. Thus, in the presence of two competing breakdown paths, as pressure is decreased, it becomes easier for an upward-directed electrical discharge to occur from the thin top layer of salt covering the anode. At lower pressures, even though the distance from the salt top to the ionospheric cathode plate is large, the *E*-field intensity in the air above the positive salt charge center is high enough and the mean free path of electrons long enough to permit discharges. An enhancement of *E*-fields just outside a cloud[26] and more recently outside an electrified dielectric[27] has been suggested and corroborates the purpose of salt crystals.

Since conductivity of substances covers an enormous range, from insulators to conductors, there are probably many particulate crystalline dielectrics that could give a response similar to salt. However, because of its white color, salt facilitated simulation of light scattering from intracloud lightning, and discharges within and near it appeared like those observed in real storms. Though it was found that small salt crystals gave good visual representation of the simulated high-altitude discharges, other dielectrics like sand with fine crystalline structure and ~70-μm diameter spherical glass beads gave similar effects, although less dramatic. For glass beads, polarization effects were minimized due to the particles' spherical shape and their low conductivity. In this case, very high *E*-fields, higher than that used for salt, had to be generated before any discharges occurred. Also, fine soil, flour, and moist salt gave no detectable visual sporadic discharge, as these were better conductors, allowing continuous current flow with little or no buildup of a charge. Depending on conductivity of dielectrics and chamber pressure used, different threshold *E*-field strengths were required for various electrical discharges. Increasing conductivity for the salt-like dielectric crystals would lower the threshold *E*-fields required for discharges in the simulation.

Finally big salt crystals (before pulverizing) strongly inhibited formation of jet simulation while only slightly inhibiting formation of sprite simulation. This was probably due to less packing structure of the ~400-μm salt crystals. Electrical discharge between electrodes, as a function of pressure, is easier for air than for big salt crystals by a factor ~2, and pulverized salt is even harder to cause a discharge, by a factor of ~3. Consequently, for big salt crystals, there were sufficient amounts of air between the crystals to keep discharge within the salt, thus inhibiting the flow of charges to the ionospheric plate. Whereas, for pulverized salt with greater packing structure, it is harder to cause discharge within the salt for substantial buildup of E-fields and the discharges in the simulation are preferred.

The salt layer thickness above the anode had a significant impact on the occurrence of these discharges. For both simulation experiments, if the anode was exposed (even a little bit) continuous flow of electrical discharge was observed, equivalent to the discharge between two electrodes having only air between them. If the overlying salt layer was too thick, no discharges above the salt top occurred. If the salt was removed, discharges in air only occurred in air between the anode and cathode closest to each other, and did not occur toward the more distant metallic plate, either with or without suspended wires. It is extremely difficult to accurately estimate the ice cloud thickness required to shield the intense positive-charge center due to variability from cloud to cloud, but a rough inference from the simulation can be made. From scaling of salt top to ionospheric plate, a distance of 1 cm may represent roughly 10 km in the atmosphere. Hence, a thickness of ~5-mm shielding provided by salt crystals could roughly scale to 5-km cloud thickness. But, the breakdown threshold E-field intensity of ~1,000 to 600 kV/m in salt crystals may be considered up to ~10 times larger than that found in thunderclouds,[23–25] which may imply that salt crystal conductivity simulated in this experiment could be a factor of up to ~10 smaller (though still in the highly variable cloud conductivity range) with more shielding effect than the dispersed ice particles in thunderclouds. Therefore, for ice cloud with the 10 times greater conductivity of ice, $^1/_{10}$ of 5 km may be required for a similar shielding or resistive effect, suggesting that the positive-charge center needed for jets could be about ~$^1/_2$-km deep within the thundercloud top. This figure constitutes a preliminary speculation which needs to be corroborated with detailed experimental comparison of the conductivity of salt crystals and ice particle distributions in cloud tops.

IV. CONCLUSION

From the experimental simulation of high-altitude cloud-ionosphere discharges using a leaky dielectric medium, several plausible criteria for the formation of jets and sprites may be hypothesized. Figure 6 shows a summarized schematic of these high-altitude discharges above thunderclouds. It is well known that separation of charges within thunderclouds causes their tops to acquire a positive charge. Also, these upper-level charge centers may be modified and redistributed by cloud updrafts, downdrafts, divergence, vertical shear, intracloud lightning, and anvil lightning. For cloud-ionosphere lightning, the position of the top charge center appears to be quite important if the experimental results are any indication. From this first simulation experiment, it is difficult to quantify the amount of shielding required in the thundercloud tops since the ice particle size, concentration, and exact conductivity of the ice-air medium varies considerably. However, this lightning probably occurs most easily when there are transiently localized regions of intense space charge built up very near the top layer of the thundercloud.

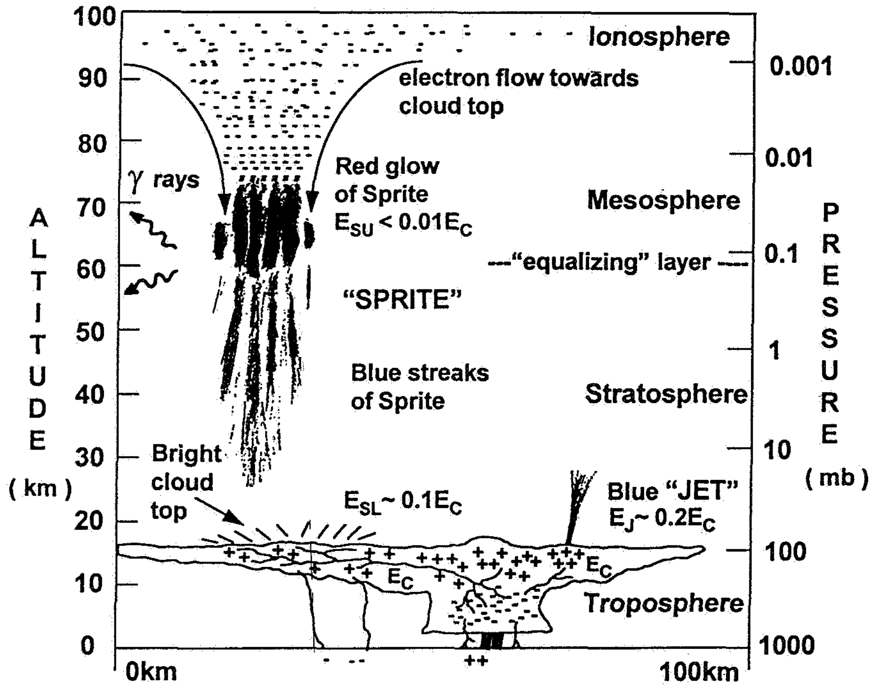

Figure 6. Schematic of jets and sprites, summarizing some fundamental characteristics of both types of discharges inferred from observations and simulation.

For jets, the positive-charge centers are probably below the physical thundercloud top boundary. If they are buried too deep, leakage above the thundercloud may be inhibited; hence, buildup of charge would occur primarily within the thunderclouds, resulting in intracloud lightning. On the other hand, if they are residing at the very top surface of the thundercloud, they would be exposed to a continuous flow of charges to and from the ionosphere, with little or no buildup of charge. In this case, sporadic high-altitude discharges may likely not be seen. The shielding or resistive effect of salt in this simulation shows that ~$^1/_2$ km of cloud shielding may be required, taking into account the difference of the breakdown threshold of salt, air, and thunderclouds. Preferred regions of the thundercloud top boundary may be created due to the combined influence of intracloud lightning close to the cloud top, mesosphere/ionosphere, and cloud dynamics. This may be enabling a positive charge to leak out in a squirt or burst. These would fan out at low pressures higher in the atmosphere until they are completely neutralized by the free electrons and ions above.

For sprites, the charge position is probably quite close to the cloud top boundary but without complete exposure, with intermittent intense bright discharge in the thundercloud top layer observed both in the atmosphere and the simulation. This cloud discharge may be bright cloud top lightning that has been occasionally reported with the sprite. This occurred in the salt when the positive-charge center was partially shielded from the cloud's main negative charge center. These conditions may be facilitated in large, vertically sheared thundercloud anvils, which can contain strong positive-charge centers displaced horizontally from the storm updraft and therefore partially shielded from the main cloud negative charges (fig. 6). Branched (spider-type) lightning discharges and positive cloud-to-ground lightning have been observed in the cloud anvils along with the occurrence of sprites.[7–9] Directly above the bright cloud top lightning, currents and E-field strengths could be transiently much higher than over other regions of thunderclouds containing no strong positive-charge centers. In response to the extreme electrically active thundercloud top positive charge and associated changes in E-fields, electrons and negative ions in the mesosphere/ionosphere are probably being pulled toward it. This process of charge motion, though physically unbounded, may be similar to the case of a thundercloud base inducing opposite charge on the Earth below and concentrating it at tall buildings, trees, and lightning rods. These highly mobile electrons in the mesosphere could create transient localized elongated conducting columns of higher electron concentration with enhanced E-fields, producing a discharge. This may be seen in the elongated upper red glow associated with sprites and the similar wire glow in the low-pressure simulation. These mesospheric discharges and the bright cloud top lightning most likely occur together, but may or may not visually connect with a sprite as seen both in the simulation and atmospheric observations. Occasionally, the streamers in the sprite do not visually connect with the bright cloud top due to the electrons and ions not having enough kinetic energy to ionize this region of higher pressure (~ 50 to 10 mb corresponding to altitudes of ~20 to 35 km) above the thundercloud. In the charge transfer within a sprite, probably the electrons and negative ions in the red sprite top descending from the mesosphere/ionosphere meet the rising positive charges from the cloud top in the tenuous blue part of the sprite. A slightly darkened region (analogous to the Faraday dark space between the negative glow and positive column of a low-pressure gaseous discharge (figs. 5(c-f)) of neutralization may thus be expected as part of a sprite just below the bright upper column glow (fig. 1(b)).[5, 7–15]

It is possible that the top red glow of the sprite may be located in the region of the "equalizing" layer of the lower mesosphere at altitudes of 60 to 70 km where enhanced E-fields have already been found to exist,[25, 28] and the density of highly mobile electrons increases while that of slower moving negative ions decreases with increasing altitude. If this is so, then recent estimates of the altitudes of the red glow of sprites[10] may provide evidence of the altitude of the "equalizing" layer. Also, it is possible that the enhanced E-fields in the "equalizing" layer of the mesosphere may assist in focusing the motion of electrons from the upper mesosphere and possibly lower ionosphere in response to thundercloud charge. This concentration of electron flow may cause intense heat, and shock waves could possibly be produced that may be the characteristic "popping" sound heard in sprite occurrence.[5] Similar, though quite faint, sound was heard from the generation of discharge in the sprite simulation. Further, recent modeling of thundercloud electric fields into the ionosphere have shown[29] that the electrified cloud can provide localized fields aligned vertically to and in the ionosphere, which may support the use of the vertical wires in this simulation and the hypothesis of the "thundercloud-modified mesosphere" for extremely intense active storms.

With high E-fields and strong currents prevalent before the discharge, the sprite may also be expected to develop more rapidly than the jets that appear to be positive charges ejected out of the cloud with no visible lower ionospheric activity. Further, the rapid movement of electrons in the thundercloud-modified mesospheric region during sprites could also be analogous to what would occur in a linear accelerator 10's of kilometers long in near vacuum conditions (especially where the electron flow is being concentrated in the elongated upper glowing red column of the sprite to near point discharge intensity). In the low-pressure simulation, the glow along the wire, analogous to upper sprite glow, occurred at $E_{su} \sim 10$ kV/m at $p \sim 1$ mb. However, in all simulated discharges, E-field values were a factor of ~10 higher than found in nature. Hence, probably $E_{su} < 1$ kV/m may be present at the onset of a sprite in the thundercloud-modified mesospheric region at $p \sim 0.1$ mb, which is even lower than achieved in simulation. This value compares well with an E-field strength estimate of 500 V/m (ref. 30), which would be sufficient for electrons to reach kinetic energies large enough to cause collisions with ions, producing gamma radiation. Such energetic gamma radiation has been observed already and has been tentatively identified with high-altitude lightning discharges.[30] In small lab-scale discharge tubes, it is well known that intense cathode glow (similar to the simulated wire glow) is capable of producing energetic electrons that can create x rays; therefore, in the intense, elongated (~10 km) upper portion of sprite glow, electrons may be capable of being accelerated to the required megaelectron volt energies to create gamma rays.

The experimental results could produce even more realistic simulation of cloud-ionosphere lightning if a vertical pressure gradient and thus a vertical conductivity gradient could be achieved.

The pressure at the tops of highly active thunderstorms is frequently around 200 to 100 mb, and these high-altitude discharges cover great distances, experiencing pressure differences spanning nearly three orders of magnitude in the upper atmosphere. Thus, the discharge characteristics within jets and sprites are expected to change significantly with decrease in pressure and will be different from lightning at much lower altitudes. Thus, the differing characteristics of the simulated discharges with those of the observed jets and sprites (narrow versus more diffuse) may be partially due to the extent of the changing air pressure above thundercloud tops (~100 to ~10 mb for jets and ~100 to ~0.1 mb for sprites).

There is much scientific interest in these high-altitude cloud-ionosphere lightning discharges. Their impact on the physico-chemistry of the middle and upper atmosphere is currently not understood because the characteristic colors of sprite glows are probably due to the complex stratospheric chemistry involving lines of various ionized gaseous species. Although the current flow from thundercloud tops to the ionosphere has been documented at various times by high-level aircraft and balloon soundings, the current flow and E-fields in these discharges may be enhanced. Future field missions making detailed analysis of these discharges with specialized instrumentation, e.g., detectors measuring current flow, E-fields, spectral characteristics, and also gamma rays, may yield a greater understanding of them.

This experiment, with the unique use of crystalline dielectric, allows realistic simulation of simultaneous above-cloud and intracloud discharges. Since the above-cloud discharges are not well understood, this technique can allow future laboratory measurements of current flow, charge transfer, spectroscopy with inclusion of stratospheric gases and ions, radioactive sources, and other atmospheric parameters that would help in modeling, parameterization, and prediction of these events. Though the experiment is straightforward, the unique ability to simulate some aspects of these discharges in the laboratory may help future research and enable further quantification of some inferences made here.

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APPENDIX A

Measurements of dielectric properties as function of electromagnetic frequency are usually published in terms of the loss tangent and the real dielectric constant or permittivity. From this information, other constants of the dielectric can be determined. Conductivity, σ, in particular is given by:

$$\sigma = \omega\varepsilon'' ,$$

where ω is the angular frequency of electromagnetic radiation and ε'' is the dielectric loss factor which is the imaginary part of the complex permittivity ε^* given by:

$$\varepsilon^* = \varepsilon' - i\varepsilon'' ,$$

where ε' is the real dielectric constant. The loss tangent is given as:

$$\tan\delta = \frac{\varepsilon''/\varepsilon_o}{\varepsilon'/\varepsilon_o} ,$$

where ε_o is the permittivity of free space given by 8.85×10^{-14} s mho/cm. Conductivity can now be written as

$$\sigma = \omega\left(\frac{\varepsilon''}{\varepsilon_o}\right)\varepsilon_o = \omega\left(\frac{\varepsilon'}{\varepsilon_o}\right)\varepsilon_o \tan\delta = 2\pi\nu\left(\frac{\varepsilon'}{\varepsilon_o}\right)\varepsilon_o \tan\delta ,$$

or

$$\sigma = \frac{\nu\left(\frac{\varepsilon'}{\varepsilon_o}\right)\tan\delta}{1.8\times10^{12}\ \text{cm/s mho}} .$$

For salt and for $\nu = 1\ Hz$ (corresponding to 1 discharge/second), $\varepsilon'/\varepsilon_o \sim 5.9$, $\tan\delta < 10^{-4}$, then

$$\sigma \sim 3.3 \times 10^{-14}\ \text{mho m}^{-1} .$$

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APPENDIX B

Electrical breakdown of air and pulverized salt crystals were separately investigated as a function of pressure, p, between two wire electrodes placed at a distance $d = 1.5$ cm from each other (fig. 7) in order to determine breakdown threshold E-field and pressure p at which discharges can be expected to occur above the salt. The breakdown E-field for salt shows considerably more scatter than that for air, which may be due to the increased polarization effects of the salt crystals under the E-fields. For the pressure regime investigated, the breakdown E-field is approximately linearly proportional to p even though there is some scatter in the data; the least-squares fit line to the data is shown. From figure 7, an estimation of the E-field above the salt, E_a, in terms of the E-field in the salt, E_s, can be determined for the experimental arrangement in figure 2. Taking into account that the separation of the cathode electrodes from the anode are in ratio 1:5, the measured decrease of E-fields from point-point electrode discharge to the point-plate electrode discharge as a function of p is a factor of ~2, and the measured decrease of E-fields from point-point electrode discharge in air and with that in the presence of pulverized salt is a factor of ~3 (fig. 7), then it can be easily shown that $E_a \sim (3/2\times5)\ E_s$ or ~1/3 E_s. This line (dashed) is also drawn in figure 7. For $p > 250$ mb, the E-field, E_a, is the above the salt is less than the E-field needed for air breakdown; therefore, discharge does not occur in the air above the salt and the E-field, E_s, within the salt is reached first, facilitating discharge within the salt. However, for $p < 250$ mb, the E-field in the air above the salt, E_a, is greater than that needed for the breakdown of air; hence, discharges occur in the air above the salt before the breakdown E-field, E_s, is reached within the salt.

A more crude approximation to the transition of discharges from inside to outside of salt as a function of pressure can also be made from figure 7. From the linear least-squares fit data shown, the breakdown E-field for salt and air is approximately proportion to (pd) and given by for salt:

$$E_{\mathrm{salt}} \sim 80\ \mathrm{kVmb^{-1}\ m^{-2}}\ (pd) + 300\ \mathrm{kVm^{-1}}\ ,$$

and for air:

$$E_{\mathrm{air}} \sim 50\ \mathrm{kVmb^{-1}\ m^{-2}}\ (pd) + 50\ \mathrm{kVm^{-1}}\ .$$

Using this for jet-type simulation where electrode distance in salt $d_{\mathrm{salt}} \sim 1.0$ cm and distance in air, between anode and ionospheric plate, $d_{\mathrm{air}} \sim 5.0$ cm, the pressure at which the discharge would begin to occur in the air toward the ionospheric plate is given by the transition pressure when $E_{\mathrm{salt}} = E_{\mathrm{air}}$, which gives $p_{(\mathrm{for\ jets})} = 150$ mb±50 mb. This is in good agreement with the range of pressure of 300 to 100 mb required for jet simulation in the experiment.

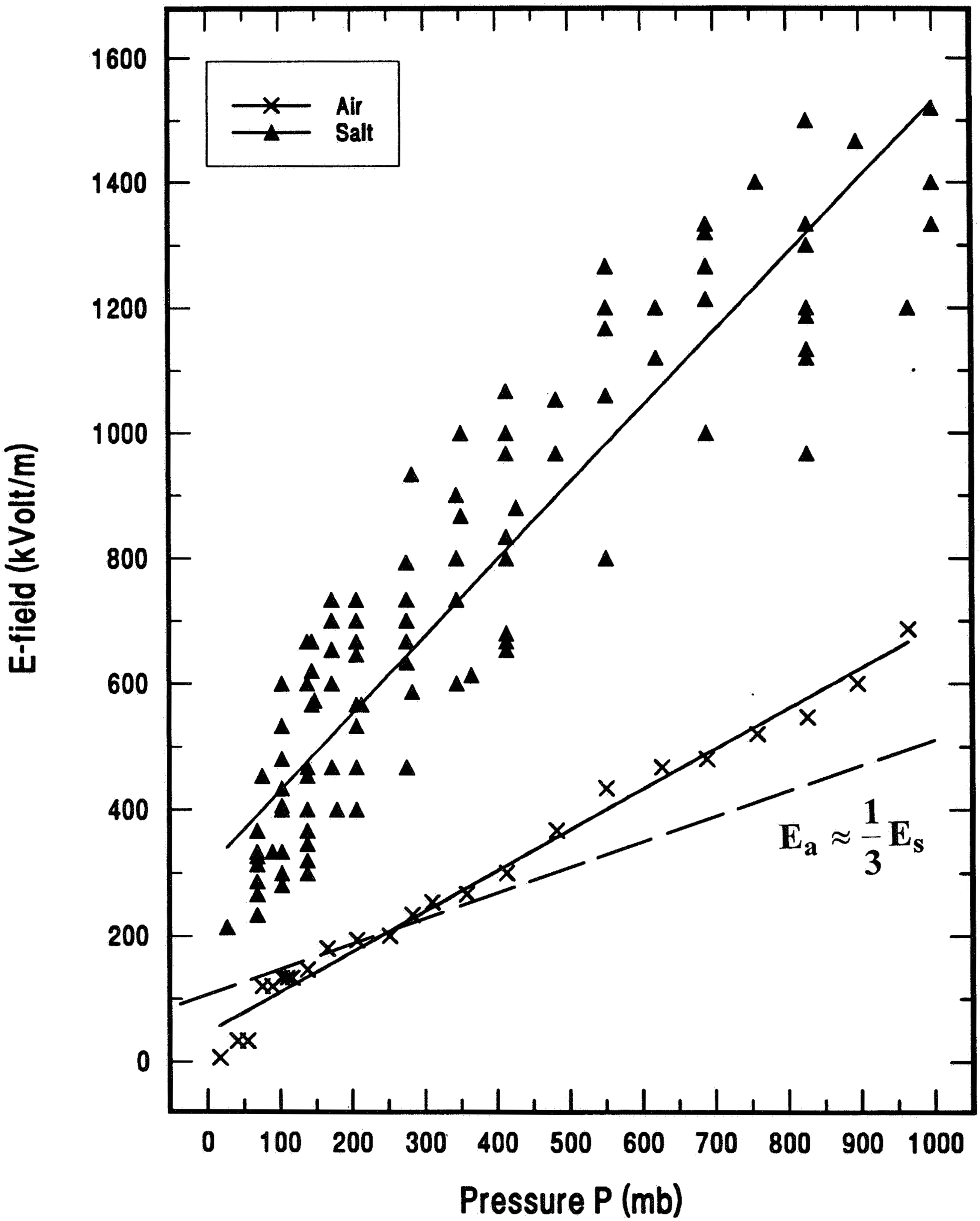

Figure 7. Breakdown threshold of air, E_{air}, and salt, E_s, as a function of pressure, p, between two wire electrodes separated a distance of $d = 0.015$ m. The estimated E-field above the salt, E_a, is shown as the dashed line.

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Recently, extremely interesting high-altitude cloud-ionosphere electrical discharges, like lightning above thunderstorms, have been observed from NASA's space shuttle missions and during airborne and ground-based experiments. To understand these discharges, a new experiment was con ceived to simulate a thundercloud in a vacuum chamber using a dielectric in particulate form into which electrodes were inserted to create charge centers analogous to those in an electrified cloud. To represent the ionosphere, a conducting medium (metallic plate) was introduced at the top of the chamber. It was found that for different pressures between ~1 and 300 mb, corresponding to various upper atmospheric altitudes, different discharges occurred above the simulated thundercloud, and these bore a remarkable similarity to the observed atmospheric phenomena. At pressures greater than 300 mb, these discharges were rare and only discharges within the simulated thundercloud were observed. Use of a particulate dielectric was critical for the successful simulation of the high-altitude lightning.

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