Role of Corona Space Charge in Electrification of Convective Thunderclouds

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(Manuscript received April 19, 1984; in revised form June 11, 1984)

Abstract

The growth rate and maximum value of electric field inside the thundercloud of finite dimensions are calculated incorporating the effect of positive space charge produced by corona at the ground surface. Our theoretical findings reveal that the transport of corona space charge increases significantly electric dipole moment already existing in thunderclouds of moderate heights and is partly responsible for their electrification.

1. Introduction

The positive space charge is produced by corona near the ground surface when the electric field is intense as it often is under thunderclouds [Livingston and Krider (1978), Standler and Winn (1979), Chauzy and Raizonville (1980), Winn et al. (1981)]. Standler and Winn (1979) reported that the rate of ions production by corona is a rapidly increasing function of the ambient electric field at the ground surface, and an estimated threshold value of electric field at the ground surface to initiate corona is about 5 KVm⁻¹.

Several investigators [Schonland (1928), Wormell (1930), Grenet (1947), Malan and Schonland (1951), Vonnegut (1955, 1965), Wilson (1956), Livingston and Krider (1978)] postulated that ions produced by corona at the ground surface are transported to the thunderclouds by updrafts which affect their electrification processes. The experiments conducted by Vonnegut et al. (1962) showed that space charge released near the ground surface is readily carried by updraft into the upper portion of thundercloud and charge of the opposite sign (screening charge) was descending around the outer portion of the thundercloud with downdraft. It was stated that same process will take place in thundercloud and much large flux of the space charge produced by corona from elevated objects at ground would eventually be carried by updraft into the thundercloud. Here it would supplement other sources of positive space charge and help to maintain and intensity the electrification of the mature thundercloud.

Moreover, Moore and Vonnegut (1977) citing the work of various investigators concluded that most convective clouds are usually most active electrically. Moore et al. (1980) also postulated that the positive space charge produced by corona is transported by updraft to the upper regions of the cloud where it enhances the intensity of positive charge. This causes a greater negative current toward the cloud base. This process continues with positive feedback. Recently, Vonnegut (1983) again suggested that sources of space charge other than corona such as falling precipitation may play the primary role in early stage of the convective electrification, but space charge produced by corona at the ground could become important later on. This corona space charge is responsible to influence the electrical processes occurring in the thunderclouds.

A time dependent model for growth rates of electric field inside the thundercloud and
at the ground surface due to a thundercloud of finite dimensions with spatial inhomogeneous electric charge distribution within it, has been developed by Mathpal and Varshneya (1983). This model concludes that electric field on the ground surface depends upon electric field inside the thundercloud. Due to intense ground electric field corona space charge is produced on the ground surface which is transported to the cloud by updraft. However, their model consists of the contribution by screening space charge in electrification of thundercloud but the model does not incorporate the effect of positive corona space charge on the electric field inside the thundercloud. Thus, in this study, a general formulation incorporating above features as well as comprehensive account of corona space charge from lower side of thundercloud, is presented. The results show that the corona space charge enhances the maximum intensity of electric field inside the thundercloud in its mature stage.

2. Mathematical analysis

Following earlier investigators [Illingworth et al. (1977), Mathpal and Varshneya (1983)] we assume that the cloud has a cylindrical shape of radius $D$ and has a vertical charge distribution within it. Figure 1 shows the dimensions of thundercloud where the origin of the coordinate system lies at its centre. One may express vertical charge distribution $\rho(z')$ within thundercloud in the form [Mathpal and Varshneya (1983)]

$$\rho(z') = \rho_{0}(t)$$

for $-(L + H) \leq Z' \leq -L$,

$$= \rho_{0}(t)Z'/L$$

for $-L \leq Z' \leq L$,

$$= \rho_{0}(t)$$

for $L \leq Z' \leq (L + H)$

(1)

where $\rho_{0}(t)$ is the maximum charge density of each polarity at instant $t$ and $Z'$ is the vertical position of point $p'$ inside the thundercloud. $2L$ is the length of charging zone within the thundercloud. $2H$ is the height for positive and negative charge regions. The

$$eq. (1) \text{ represents the predominance of positive charge in the upper part, and that of negative charge in the lower part of thundercloud, as usually observed. In the intervening space the charge is linearly varying with height.}$$

The electric field inside the thundercloud, $E_{in}$ (considering point $P$ inside the cloud, Fig. 1) and the electric field at any point on the ground $E_{out}$, following Mathpal and Varshneya (1983) and including leakage current due to conduction and point discharge [Mason (1972), Ziv and Levin (1974)] are given by

$$\frac{dE_{in}}{dt} = \frac{(1-C_{2})}{\varepsilon_{0}} [J_{in}(t) + i(t)] \quad (2)$$

and

$$\frac{dE_{out}}{dt} = \frac{2\pi D^{2}}{4\pi \varepsilon_{0}} \left[ \frac{(L + H)^{2} - L_{2}^{2}/3}{(H + L/2)[d^{2} + Z^{2}]^{3/2}} \right] \cdot [J_{in}(t) + i(t)] \quad (3)$$

where $J_{in}(t)$ is the current density inside the thundercloud at instant $t$ and is given by

$$J_{in}(t) = F(t)[\alpha - F(t)E_{in}(t)\beta] + A_{1}E_{in}(t)[W - A_{2}E_{in}^{2}(t)] \quad (4a)$$

and $i(t)$ is the leakage current density at instant $t$ which is given by
where $i(t) = -10^{-8}[\exp(6.7 \times 10^{-4}E_{in}(t))-1]/3$

(4b)

The parameters used here are explained in Appendix.

Standler and Winn (1979), Chauzy and Raizonville (1980), Winn et al. (1981) reported space charge density, 1 nCm$^{-3}$, 2-4 nCm$^{-3}$ and 1.7 nCm$^{-3}$, respectively near the ground surface. Standler and Winn (1979) also established the following relation between corona current density, $J_{cr}(t)$ and ambient electric field $E_{out}(t)$, at the ground:

$$J_{cr}(t) = \begin{cases} 0 & \text{for } |E_{out}(t)| \leq E_0 \\ CE_{out}(t)[|E_{out}(t)| E_0]^2 & \text{for } |E_{out}(t)| > E_0 \end{cases}$$

(5)

where, $E_0$ is the minimum value of the electric field at the ground to initiate corona, $C$ is a function of the number of discharging objects per unit horizontal area. For a generalized case, the magnitude of estimated value of $E_0$ and $C$ are 5 KVm$^{-1}$ and $2.0 \times 10^{-20}$ AmV$^{-3}$ respectively [Standler and Winn (1979)].

Vonnegut et al. (1962) conducted an experiment and suggested an updraft of several meter per second to carry corona space charge from ground to cloud. Considering updraft velocity $U$, the positive corona space charge density, $J_s$, entering into upper positive region of thundercloud will be given by

$$J_s(Z, t_s) = neU$$

(6)

where $e$ is the elementary charge and $n$ is the number density of positive ions. $Z$ is the vertical height of the positive charge region from the ground and $t_s$ is the sum of time taken to produce corona space charge, $t_{cr}$ and the time in which corona space charge reaches upper positive region of thundercloud $t_s$, and is expressed as

$$t_s = t_{cr} + t_r$$

(6a)

where $t_r = Z/U$.

In order to get approximate value of $n$, we equate equation (6) to the relation provided by Lane-Smith (1972) and Prasad et al. (1976) i.e.

$$J_{cr}(t) = neoE_{out}(t)$$

(7)

where $o$ is the mobility of positive ions. Substituting obtained value of $n$ in eq. (6) we get

$$J_s(Z, t_s) = C[|E_{out}(t)| - E_0]^2 \frac{U}{o}$$

Further, putting $U$ in terms of $Z$ and $t_s$ from eq. (6a), we obtain

$$J_s(Z, t_s) = C[|E_{out}(t)| - E_0]^2 \frac{Z}{(t_s - t_{cr})o}$$

for $t < t_s$, $J_s(Z, t_s) = 0$ (8)

Eq. (8) shows that corona space charge can affect growth rate of electric field inside the thundercloud only in the mature stage of cloud due to time lag in production and transport of corona space charge.

Considering the contribution of corona space charge in electrification of thundercloud, the equation for the growth rate of electric field inside the thundercloud will be modified as

$$\frac{dE_{in}}{dt} = \frac{(1-C_v)}{\varepsilon_0} \left[J_{in}(t) + J_s(Z, t_s) + i(t)\right]$$

for $t < t_s$, $J_s(Z, t_s) = 0$ (9)

or

$$\frac{dE_{in}}{dt} = \frac{(1-C_v)}{\varepsilon_0} \left[F(t)[\alpha - F(t)E_{in}(t)\beta] + A_1 E_{in}(t)[W - A_1 E_{in}(t)] + C[|E_{out}(t)| - E_0]^2 \frac{Z}{o(t_s - t_{cr})} - 10^{-8}[\exp(6.7 \times 10^{-4}E_{in}(t))-1]/3\right]$$

(10)

where

$$F(t) = KF'(t)/[\exp(\langle p \rangle \cdot \frac{t}{\tau})]$$

(11)

$$F'(t) = \int_{0}^{t} E_{in}(t) \exp(\langle p \rangle \cdot \frac{t}{\tau}) dt$$

(12)

or

$$\frac{dF'(t)}{dt} = E_{in}(t) \exp(\langle p \rangle \cdot \frac{t}{\tau})$$

(13)

Earlier it has been pointed out by Whipple and Scarse (1936), and Wormell (1953) that electric field at the ground is superposition of two fields, one from charge in thundercloud and other from space charge near the ground.
Therefore, including the effect of corona space charge on the ground electric field also, equation (3) becomes

\[
\frac{dE_{\text{out}}}{dt} = \frac{2\pi D^2}{4\pi \varepsilon_0} \left[ (L+H)^2 - L^2/3 \right] \left[ (d^2 - 2Z^2) \right] \left[ H - \frac{L}{2} \right] (d^2 + Z^2)^{3/2} \cdot \left[ J_{\text{in}}(t) + J_{\text{ex}}(t) + i(t) \right] \tag{14}
\]

If, once corona space charge is produced, then it appears like a continuous process. The ions produced by corona are transported to the cloud by updraft and are also produced simultaneously on the ground surface. So, there would be continuous flux of corona space charge flowing towards the cloud which affects electric field growth rate inside the thundercloud after production and transport time lag, while ground electric field in affected instantly by this charge.

3. Results and Discussion

A computer programme was run to calculate growth rate of electric field inside the thundercloud incorporating the effect of corona space charge. For this purpose, Runge-kutta Method was used to solve equation (10). Because Equation (10) is \(E_{\text{out}}\) and \(F(t)\) dependent, therefore, equation (13) and (14) were also solved simultaneously by the same method. Downward directed electric field is considered as positive electric field. To solve these equations numerically we assume initially, when \(t=0\), \(E_{\text{out}}(t)=E_{\text{in}}(t)=100\ \text{Vm}^{-1}\) and \(F'(t)=-0\). Generally, in evaluations, we take \(L=1.5\ \text{Km}\), \(D=1.25\ \text{Km}\), \(d=0\), \(p_o=10\ \text{mmh}^{-1}\), \(f_1=f_2=0.25\), \(\tau=100\ \text{s}\), \(W=4\ \text{ms}^{-1}\) [Mathpal and Varshneya (1983)]. Following Mason (1972, 1973), Spangler and Rosenkilde (1979), an average value \(<p>=.5\) is used in the present calculations. The results of the calculation of the growth rate of electric field inside the thundercloud incorporating the effect of corona space charge for several sets of involved parameters such as \(p_o, U, W\) and \(h\) are presented in figure 2 through 5.

First, calculations are furnished in order to investigate the influence of corona space charge on the growth rate of electric field inside the thundercloud for various values of precipitation intensity, \(p_o\). The results are shown in Figure 2. It is found that corona space charge increases growth rate of electric field as well as maximum value of electric field inside the thundercloud in its mature stage. The effect is noted in the mature stage of cloud because it takes time in production of space charge and subsequently in reaching the cloud. For example, assuming \(U=10\ \text{ms}^{-1}\), \(Z=h+H+L=2.5+1.5=4\ \text{Km}\), we get \(t_r=830\ \text{s}\) and \(t_s=400\ \text{s}\) or \(t_r=1230\ \text{s}\) when \(p_o=10\ \text{mmh}^{-1}\) and \(W=4\ \text{ms}^{-1}\). Therefore, it is evident that corona space charge flux can affect the growth rate of electric field inside the thundercloud only after 1230 s due to the production and transport time lag. Since, the flux of corona space charge reaching the thundercloud increases with time (because production of charge is \(E_{\text{out}}\) dependent which increases with time), therefore, growth rate of electric field inside the thundercloud is affected significantly before reaching the maximum value of electric field \(E_{\text{max}}\), as shown in Figure 2. Considering above mentioned parameters \(E_{\text{max}}\approx 286\ \text{KVm}^{-1}\) in 1500 s and \(E_{\text{max}}\approx 345\ \text{KVm}^{-1}\) in 1780 s is obtained excluding and including the contribution of corona space charge respectively.

Figures 2 also shows that as precipitation intensity \(p_o\) increases, the starting time to affect the growth rate of electric field and the duration to affect it decreases. The maximum value of electric field inside the thundercloud \(E_{\text{max}}\), time to produce corona space charge, \(t_r\), and to reach the cloud \(t_s\), with and without corona space charge for various values of \(p_o\), are listed in Table 1.

Figure 3 illustrates the growth rate and maximum value of electric field inside the thundercloud for various values of updraft velocity, \(U\). An increase in updraft velocity reduces the transport time of corona space charge from ground to upper positive charge region of cloud and affects growth rate earlier. A higher value of updraft velocity increases the corona space charge density entering the cloud and therefore, provides higher values of maximum electric field inside the thundercloud. We obtain \(E_{\text{max}}\approx 345\ \text{KVm}^{-1}\) and \(E_{\text{max}}\approx 406\ \text{KVm}^{-1}\) for \(U=10\ \text{ms}^{-1}\) and \(U=20\ \text{ms}^{-1}\) respectively. Our results found support from
Fig. 2 Rates of growth of the electric field inside the thundercloud with and without corona space charge effect for various values of precipitation intensity $p_0$.

Fig. 3 Rates of growth of electric field inside the thundercloud with and without corona space charge effect for various values of updraft, $U$.

Fig. 4 Rates of growth of electric field inside the thundercloud with and without corona space charge effect for various values of downdraft, $W$.

Fig. 5 Rates of growth of electric field inside the thundercloud with and without corona space charge effect for various values of cloud height, $h$, from the ground.
the conclusion made by Moore and Vonnegut (1977) that most convective clouds are usually most active electrically. The results are also shown in Table 1 for various values of updraft velocity $U$.

The calculations are also performed for various values of downdraft, $W$. Figure 4 elucidates the influence of downdraft on electric field growth rate inside the thundercloud incorporating corona space charge effect. An increase in downdraft increases both electric field growth rate and maximum value of electric field including contribution of corona space charge. Table 1 indicates obtained results for various values of $W$.

Figure 5 indicates growth rate of electric field inside the thundercloud for different values of cloud height from the ground. It is evident that high clouds take more time to produce corona space charge at ground surface. Moreover, charge also takes more time to reach the cloud. Figure 5 shows that lower height clouds are affected for long duration by corona space charge. Table 1 shows results for different value of $h$.

The obtained maximum values of electric field at ground surface $(E_{\text{out}}} \text{max})$ in all calculations (table 1) are also consistent with the observations as reported by Vonnegut (1963), Livingston and Krider (1978), Standler and Winn (1979) and Winn et al. (1981) i.e. $(−5 \text{ to } −8 \text{ KVm}^{-1})$.

Finally, the concluding discussion brought out the importance of positive corona space charge in the electrification of thunderclouds. It is carried out that the transport of corona space charge from ground surface enhances the growth rate and maximum value of electric field inside the thunderclouds in its mature stage.

**Acknowledgements**

One of authors (P. Singh) wishes to express thanks to Dr. K.C. Mathpal and Dr. M.V.N. Reddy for their valuable suggestions.

**Appendix**

The expressions for $\alpha$, $\beta$, $A_1$ and $A_2$ as given by Mathpal and Varshneya (1983).

$L$ = vertical length of the charging zone on each side from the centre of cloud.

$H$ = vertical length of both upper main positive

### Table 1

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<tr>
<th>$p_0$ (mm h⁻¹)</th>
<th>$U$ (ms⁻¹)</th>
<th>$W$ (ms⁻¹)</th>
<th>$h$ (km)</th>
<th>$t_{cr}$ (s)</th>
<th>$t_z$ (s)</th>
<th>$E_{\text{max}}$ (KVm⁻¹)</th>
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and lower main negative charge regions.

\( h \) = vertical height of the cloud base from the ground surface.

\( Z \) = vertical height of the centre of cloud from the ground surface.

\( \approx \) vertical height of the positive charge region from the ground surface.

\( =H+L+h \)

\( U \) = updraft velocity

\( W \) = downdraft velocity

\( D \) = radius of cloud

\( d \) = the horizontal distance between the point of observation \( P \) and the point at the ground just below the centre of cloud.

\[ a = \frac{12\pi \varepsilon_0 N_0 \rho_w}{\rho_c} \left[ \frac{K_1}{R_c} R^3 \exp(-XR) dR \right. \]

\[ + \left. K_1 \left( \frac{R^{1/2}}{2} \right) \exp(-XR) dR \right] \]

\[ + \left. K_1 \left( \frac{R^{3/2}}{2} \right) \exp(-XR) dR \right] \]

\[ \beta = \frac{[108\pi \varepsilon_0 N_0 \rho_w / (\rho_c^3)]}{[12\pi \varepsilon_0 N_0 \rho_w / (\rho_c^3)]} \left[ \frac{K_1}{R_c} R^3 \exp(-XR) dR \right. \]

\[ + \left. K_1 \left( \frac{R^{1/2}}{2} \right) \exp(-XR) dR \right] \]

\[ + \left. K_1 \left( \frac{R^{3/2}}{2} \right) \exp(-XR) dR \right] \]

\[ A_1 = 1.2175 f_1 f_2 L \frac{\rho_w}{(\rho_c^3)} \]

\[ A_2 = 2 \times 1.2175 f_1 f_2 L \frac{\rho_w}{(\rho_c^3)} \left[ \frac{9 \mu(C_D R_e/24) a_c}{1} \right] \]

where,

\( N_0 = 0.16 \times 10^8 \text{m}^{-4} \)

\( \rho_w \) = density of water

\( \rho_c \) = density of ice \( [0.7 \times 10^3 \text{kg} \text{m}^{-3}] \)

\( \rho_e \) = density of cloud particles

\( L_w \) = liquid water content \( [4\pi a_c^3 \rho_w / 3] \)

\( X = 8200 \rho_0 \text{m}^{-1} \)

\( \rho_0 \) = precipitation intensity in mmh\(^{-1}\)

\( R_c \) = critical radius of hail particle

\( R_e \) = hail pellets radius, \( R > R_e \)

\( K_1 = 6400 \text{s}^{-1} \)

\( K_2 = 160 \text{m}^{1/2} \text{s}^{-1} ; K_3 = 150 \text{m}^{1/2} \text{s}^{-1} \)

\( \varepsilon_0 \) = permittivity of the free space

\( (C_D R_e/(2A)) a_c \) = the ratio of the gravitational force to viscous force acting on a cloud particle of radius \( a_c \)

\( \mu \) = coefficient of viscosity of air inside thundercloud

\( f_1 \) = fractional constant of electric field

\( f_2 \) = fractional constant of saturation space charge on cloud particles

\( a_c \) = radius of the cloud particle

\[ K = \sqrt{\frac{\pi}{2}} \sqrt{1+\frac{m_e}{2}} \left( \frac{m_e+3\sqrt{(m_e+3)}^2}{2} \right) m_e \]

\[ m_e = 2 \left( \frac{1-\langle\rho\rangle}{\langle\rho\rangle} \right) \]

\[ \langle\rho\rangle \] = average rebound probability

\( \tau \) = relaxation time

\( E_{in} \) = ambient electric field inside the thundercloud

\( E_{out} \) = ambient electric field on the ground surface

\[ C = \left[ \frac{(L+H)^2 + D^2}{4L} \right] \left( \frac{\langle L^2 + D^2 \rangle}{2} - \frac{L}{4L} \right) \]

\[ l_n \left[ \frac{\langle L^2 + D^2 \rangle}{2} - \frac{L}{4L} \right] \left[ \frac{H + L}{2} \right] \]

\[ R \] = radius of hail pellets, \( R > R_e \)

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\[ l_n \left[ \frac{\langle L^2 + D^2 \rangle}{2} - \frac{L}{4L} \right] \left[ \frac{H + L}{2} \right] \]

References


### 対流雷雲中の電荷生成におけるコロナ空間電荷の役割

プラタップ・シン・T.S. ヴェルマ・N.C. ヴァルシュネヤ

インド、ルーキー大学物理学科

地表におけるコロナ放電で発生する正の空間電荷の影響を考慮して、有限規模の雷雲中における電場の生長率と最大値を計算した。この計算の結果、コロナ放電で発生した空間電荷の移動は、適当な高度の雷雲中にすでに存在する電気双極子モーメントを多少増加させ、雷雲電荷生成に一定の役割を果すことがわかった。