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The origin of Electric Charge carried by Thunderstorm Rain in the Tropics*

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ABSTRACT. A detailed study of the electricity carried by thunderstorm rain has been made at the Poona Meteorological Office, during four years 1955—1958. The study consists in considering the three stages in the life history of raindrops, namely, (1) the growth of the drop within the cloud and the possible acquisition of electric charges, (2) the period of free-fall below the cloud with the possible modification of charge of rain by capture of point discharge ions as per theories advanced by Whipple and Chalmers and (3) the arrival at the ground with the possible effects of splashing at the ground. It is concluded that the electricity of thunderstorm rain is not always due to any single process of generation of charge, and that several factors such as the impact of ice crystals, the breaking of drops, as per theories advanced by Simpson and Scrase, the Wilson mechanism, and the effect of lightning discharge, may operate together to determine what shall be the sign of the charge on thunderstorm rain when it reaches the ground. It is also proved that charging of the rain due to splashing at the surface does not occur, as the rain receiver is suitably shielded to avoid splashing.

1. Introduction

The study of electricity carried by precipitation has become important in recent years in view of the conflicting theories regarding the origin of electric charge carried by raindrops. The general results up-to-date have been summaried by Chalmers (1957) and the more recent work has not altered these conclusions. Precipitation currents bring more positive than negative charge to the earth both for thunderstorm rain and for continuous rain. The study of the continuous records taken at the Instruments Section of the Meteorological Office, Poona, during the years 1955—58 using instruments, a description of which is given in detail elsewhere (Sivaramakrishnan 1959), (Figs. 1-2), show the same conclusion. Thus the general excess of positive charge by rain shows that precipitation cannot be the way in which the negative charge on the earth is maintained, but rather that precipitation currents add to the fine weather current in bringing positive charge to the earth.

The work described in this paper is based on the continuous observations made at Poona Observatory during 1955 and 1956 of (*a*) potential gradient measured by a Cambridge photographic electrograph, (*b*) the discharge current from an insulated elevated needle point at a height of 17·8 metres above the ground using a Moll galvanometer, (*c*) the charge carried by the rain using a photographic rain electrograph and (*d*) the rate of rainfall using a tilting bucket raingauge and Bibby type impulse recorder.

2. Results and conclusions of observations on the electricity carried by thunderstorm rain

A complete description and conclusions of observations on the electricity carried by thunderstorm rain have been given in detail elsewhere (Sivaramakrishnan 1959). A brief summary of the results is given below— .

(1) From the records, values of the following quantities were obtained for each minute during periods of disturbed weather :—

(*a*) Potential gradient P (v/cm), (*b*) Point-discharge current I (e.s.u./sec), (*c*) Rain current i (e.s.u./cm^2/sec), (*d*) Charge per cubic centimetre carried by the rain q (e.s.u./cm^3),

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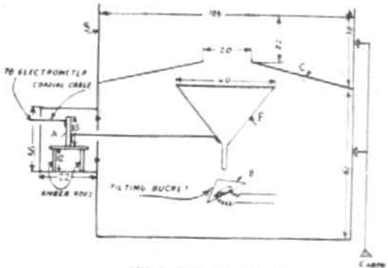
*This paper forms part of the results of a doctoral dissertation (Part VI and Part VIII) of the Ph. D. thesis submitted to the University of Madras in January 1959. Details of the measurement, computation techniques, further elaboration of the results, limitations etc are given in that thesis.

This paper was also presented at the Symposium on "Thunderstorms" held at New Delhi from 9 to 11 March 1960



(ALL DIMENSIONS ARE IN CMS)

A INSULATED STAND SUPPORTING FUNNEL
B TILTING BUCKET RAINGAUGE
C CONICAL SHIELD
F INSULATED FUNNEL
S OUTER CYLINDRICAL SHIELD

FIG 1. RAIN RECEIVER AND TILTING BUCKET

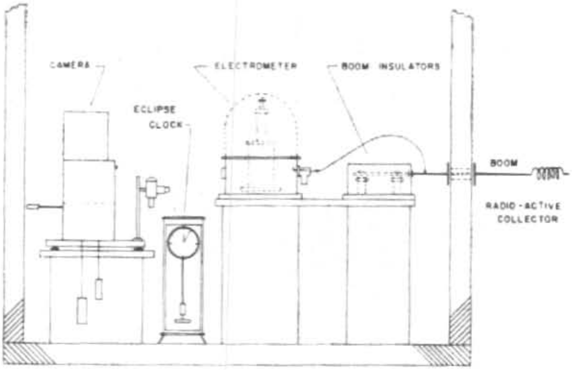


FIG 2 RELATIVE POSITIONS OF THE VARIOUS PARTS OF THE ELECTROGRAPH IN THE RECORDING HUT

and (*e*) Rate of rainfall R (cm/sec) or R' (mm/hour), ($R'=3\cdot 6\times 10^4 R$).

(2) The relationship between the electricity carried by precipitation and the potential gradient is entirely different for gradients greater than 6 volts/cm (generally found for thunderstorms) from what it is for gradients less than 6 volts/cm. It is, therefore, necessary to consider the two cases separately and in this paper the former case is considered.

(3) There is always a current of electricity into the air from the needle point erected at a height of 17·8 metres from the ground at Poona Observatory, when the potential gradient is greater than 6 v/cm. When the curves for the field P, point discharge current I, and rain current i are examined, it is noticed that the sign of rain electricity i or q is practically found opposite to the sign of the field. The curves sometimes cross the zero line together but in opposite directions (Figs. 3, 4 and 5). This Simpson calls as the 'mirror image' effect.

(4) When we plot log i and log I with the rate of rainfall R' marked against each point, the points form a band making an angle of 45° with the abscissa showing that the average i is a linear function of I with the higher values of R' appearing along the upper edge of the band (Fig. 6). Thus, for any given value of R', we have

i=a constant$\times I$, the constant being different for each value of R',

or $\quad i=f R' . I.$

(5) By purely empirical methods, the observations can be represented by the following expressions—

$$i/I=9\cdot 734\times 10^{-8}\times R'^{0\cdot 665} \qquad (1)$$

$$i/I=0\cdot 8\times 10^{-6}\,(1-e^{-0\cdot 093R'}) \qquad (2)$$

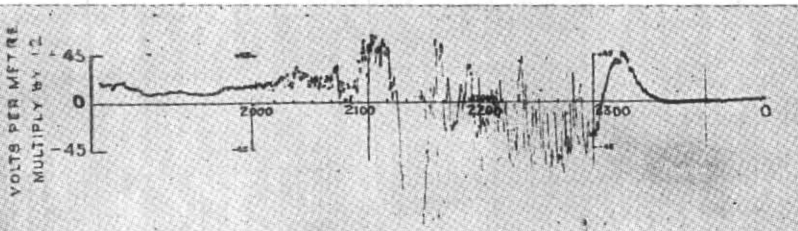
$$i/I=1\cdot 61\times 10^{-6}\left(\frac{R'}{R'+6}\right) \qquad (3)$$

(6) In order to verify whether the mean values of i/I are correlated with R', correlation coefficients between R' and i/I have been determined for the following cases—

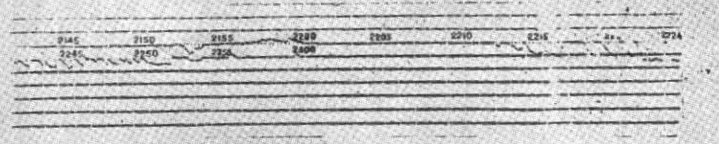
Variable	*Correlation coefficient*
(Mean $i/I - R'$)	
(1—15 mm/hr)	·65
(20—90 mm/hr)	·51
(1—90 mm/hr)	·73

From this we can say that the mean i/I and R' is highly correlated and so the conclusion to be drawn is that a physical relationship exists between i/I and R'.

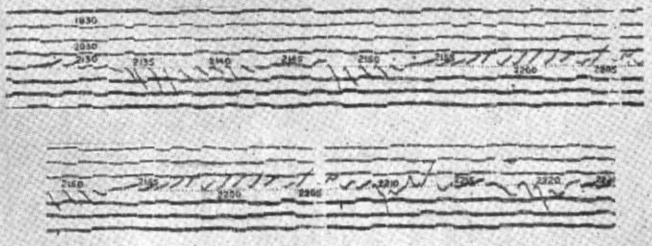
(7) It is deduced from observations that at Poona for potential gradients >6 v/cm, (*a*) the rain current i derives its charge from the natural point discharge current J, (*b*) with a given rate of rainfall R' the rain current increases and decreases with the point discharge current and (*c*) with the constant point discharge current the rain current increases and decreases with the rate of rainfall (Fig. 6).



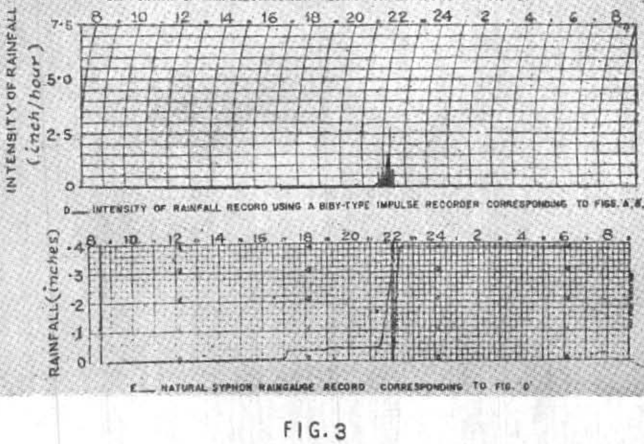
A_ PORTION OF ELECTROGRAPH RECORD DURING A THUNDERSTORM AT POONA ON 5-6 OCT 1956.



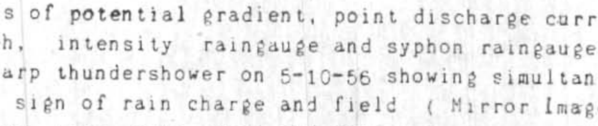
B_ PORTION OF POINT DISCHARGE RECORD CORRESPONDING TO FIG. 'A'



C_ PORTION OF RAIN ELECTROGRAPH RECORD CORRESPONDING TO FIG. 'B'



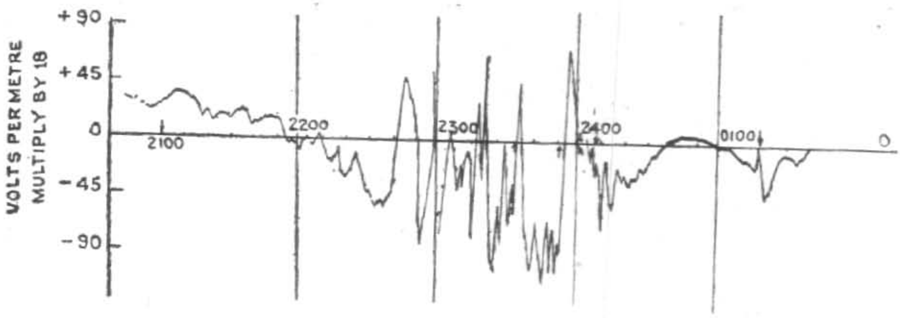
D_ INTENSITY OF RAINFALL RECORD USING A BIBY-TYPE IMPULSE RECORDER CORRESPONDING TO FIGS. A, B, C.



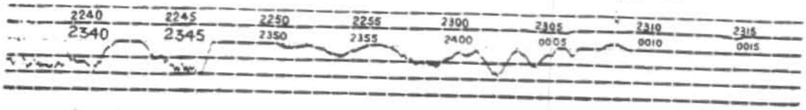
E_ NATURAL SYPHON RAINGAUGE RECORD CORRESPONDING TO FIG. 'D'

FIG. 3

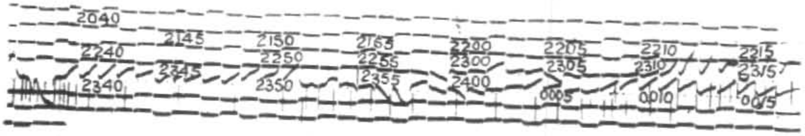
Portions of potential gradient, point discharge current, rain electrograph, intensity raingauge and syphon raingauge records during a sharp thundershower on 5-10-56 showing simultaneous changes in the sign of rain charge and field (Mirror Image Effect) at 2130, 2132, 2146, 2155, 2210 and 2220 hrs. No point discharge current was noticed between 2130 hours and 2211 hours, but the sign of the rain charge is found to be negative between 2133 and 2142 hours and 2147 and 2151 hours. showing that the thunder rain has come from the cloud with the negative charge as Wilson's mechanism is not effective to change the negative sign to positive.



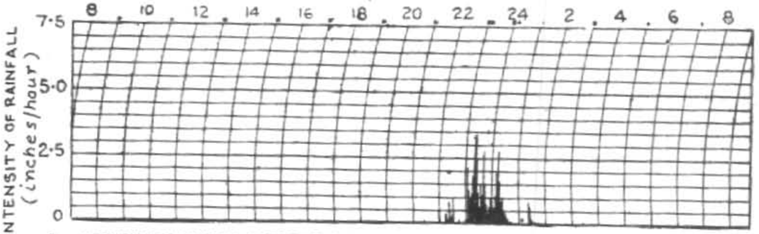
A—PORTION OF ELECTROGRAPH RECORD DURING A THUNDERSTORM AT POONA ON 1-2 OCT 1956



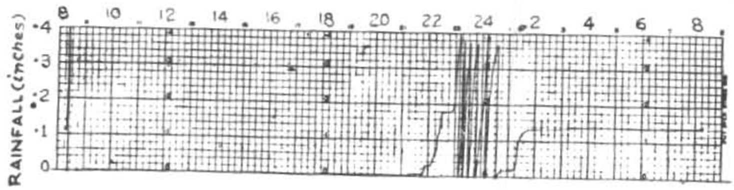
B—PORTION OF POINT DISCHARGE RECORD CORRESPONDING TO FIG 'A'



C— PORTION OF RAIN ELECTROGRAPH RECORD CORRESPONDING TO FIG 'B'



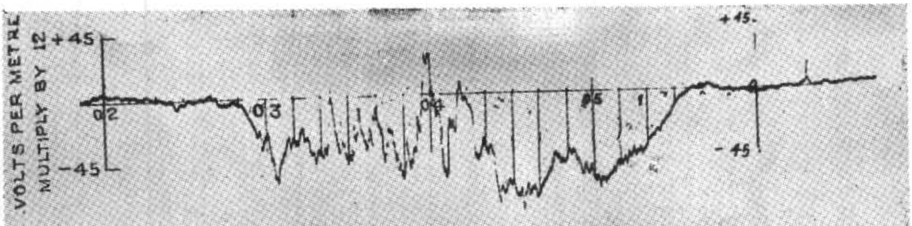
D— INTENSITY OF RAINFALL RECORD USING A BIBY-TYPE IMPULSE RECORDER CORRESPONDING TO FIGS. A, B, C.



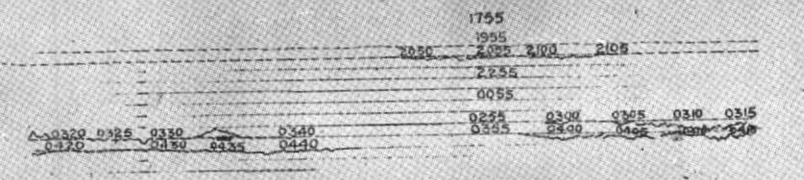
E— NATURAL SYPHON RAINGAUGE RECORD CORRESPONDING TO FIG. 'D'

FIG. 4

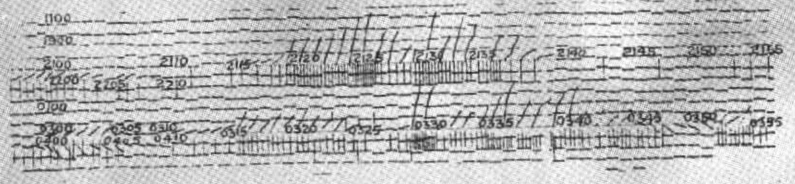
Portions of potential gradient, point discharge current rain electrograph, intensity rainguage and syphon raingauge records during a thunderstorm on 1-2 October 1956, showing simultaneous changes in the sign of the rain charge and field (Mirror Image Effect) at 2259, 2300, 2310, 2336, 2339, 2355 and 0008 hours. No point discharge current was noticed between 2310 hours and 2317 hours, but the sign of the thunderstorm rain is found to be positive, without Wilson's mechanism being effective during these times.



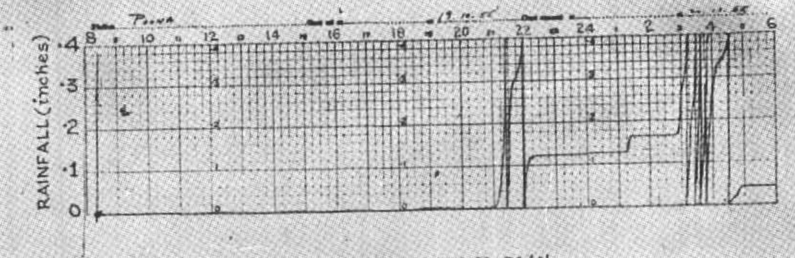
A— PORTION OF ELECTROGRAPH RECORD DURING A THUNDERSTORM AT POONA 19-20 OCT 55



B— PORTION OF THE POINT DISCHARGE RECORD CORRESPONDING TO—A. SCALE ↕ = MICROAMPERE ↑ POSITIVE



C— PORTION OF RAIN ELECTROGRAPH RECORD CORRESPONDING TO—A AND B, ↑ POSITIVE



D— NATURAL SYPHON RAINGAUGE RECORD CORRESPONDING TO FIG. 'C'

FIG. 5

Another example of mirror image effect showing positive rain charge and negative field between 0300 and 0500 hours during a thunderstorm on 20 October 1955. The time lag between the field change (Positive to zero and negative) at 0242 hours and the onset of rain at the surface at 0255 hours, is 15 minutes. The intensity of rain being 15 mm / hr at the start and assuming a terminal velocity of 4.8 meters per second, the distance of fall of raindrops is found to be 15 X 60 X 4. meters or approximately 4320 meters

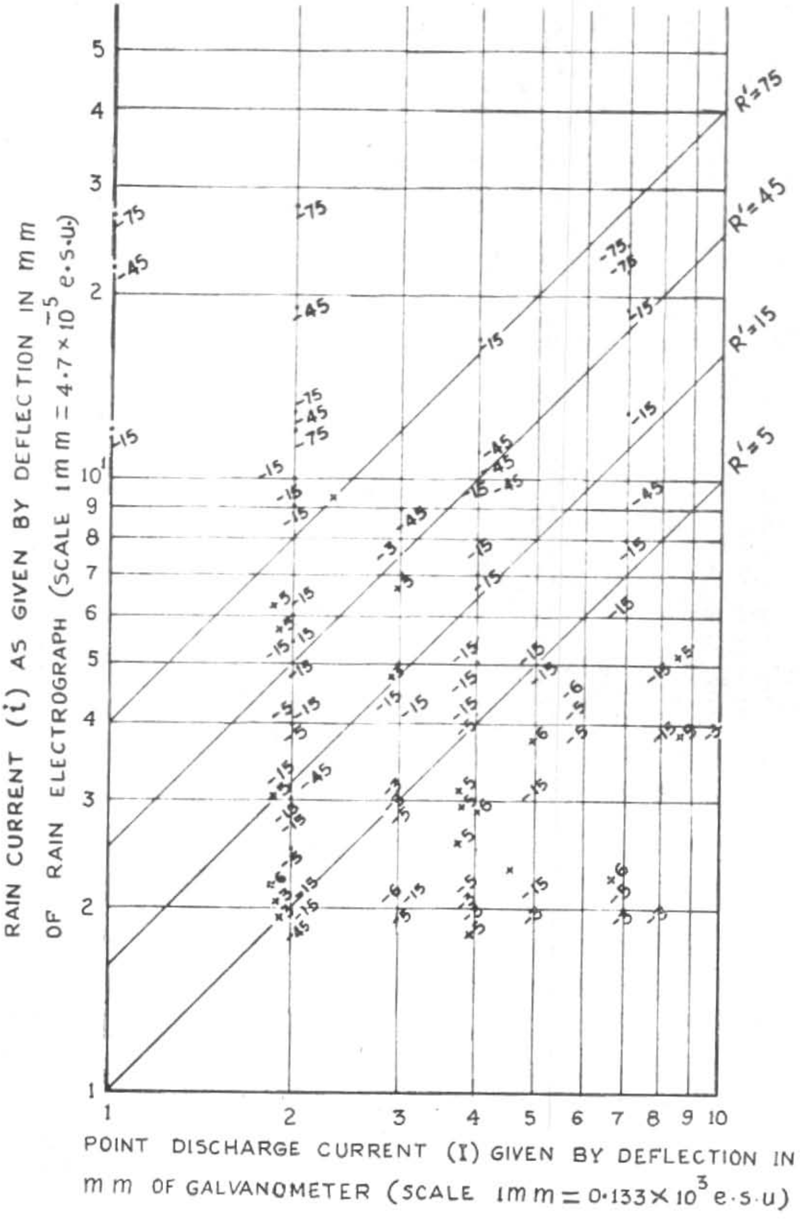

RAIN CURRENT (i) AS GIVEN BY DEFLECTION IN mm
OF RAIN ELECTROGRAPH (SCALE 1mm = 4·7 × 10^{-5} e·s·u.)
POINT DISCHARGE CURRENT (I) GIVEN BY DEFLECTION IN
mm OF GALVANOMETER (SCALE 1mm = 0·133 × 10^{3} e·s·u)
R'=75
R'=45
R'=15
R'=5
1
2
3
4
5
6
7
8
9
10^1
2
3
4
5
1
2
3
4
5
6
7
8
9
10

FIG. 6

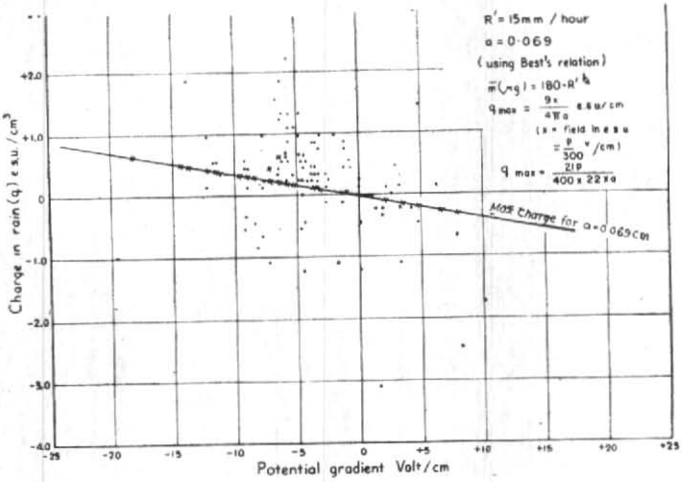


FIG 7

(8) Assuming that the current through the needle point I at the Poona Observatory is $\propto$ to the natural point discharge current J then $I = AJ$ in which A is the 'equivalent area' of the needle point, *i.e.*, the area of country surroundings of Poona Observatory from which the total natural point discharge current is equal to the current through the needle. Also when $R' = 0$, $i = 0$, and, when $R' = \infty$, $i = J$. In heavy rainfall, all the ions from the point discharge are absorbed by the rainfall and the rain current becomes equal to the natural point discharge current.

In this limit,

Equation (2) gives $A = 1 \cdot 25 \times 10^6$ cm²
Equation (3) gives $A = 0 \cdot 63 \times 10^6$ cm²

giving average $A = 0 \cdot 94 \times 10^6$ cm² as compared with Kew where $A = 5 \cdot 5 \times 10^6$ cm² and 4×10^6 cm² respectively.

(9) The effective spacing l of discharging points at Poona is given by $l = \sqrt{A} = \sqrt{\cdot 94 \times 10^6} = 1000$ cm (approx.) or 10 metres. The effective spacing l at Kew $= 22$ metres (Simpson 1949) and the effective spacing l at Durham $= 6 \cdot 1$ metres (Chalmers 1951).

(10) When we try to explain as to how the raindrops acquire their charge, grave difficulties are encountered. The results obtained at Poona appear to be in general agreement with Simpson as regards the ion-capture process suggested by Wilson and worked out in great detail by Whipple and Chalmers. The theory worked out by Whipple and Chalmers (1944) shows that the maximum charge in a drop of radius a in a field X with ions of one sign only present is $-3Xa^2$. But when we compare the actual drop charges a or charge per c.c. of rain q with the theoretical maximum values $-3Xa^2$, or $-9X/4\,\pi\,a$ the actual charges are sometimes found five or six times more than the theoretical maximum (Fig. 7). This shows conclusively that the drops cannot have acquired their charge by Wilson's process if the field is everywhere the same as at the ground. If the rain receives its charge in the upper air where the fields are supposed to be greater, owing to the formation of the blanket charge, it is difficult to see how the charge on the rain can vary simultaneously with the field at the ground (mirror image effect of Simpson).

(11) The charge per single raindrop at Poona is calculated using Best's relation (1947) between rate of rainfall R' and average mass per raindrop $\bar{m}$ and modified by Browne, Palmer and Wormell (1954), *i.e.*,

$$\bar{m}\,(\mu g) = 180\; R'^{3/4} \qquad (4)$$

where $\bar{m}$=mean mass of raindrop in microgramme.

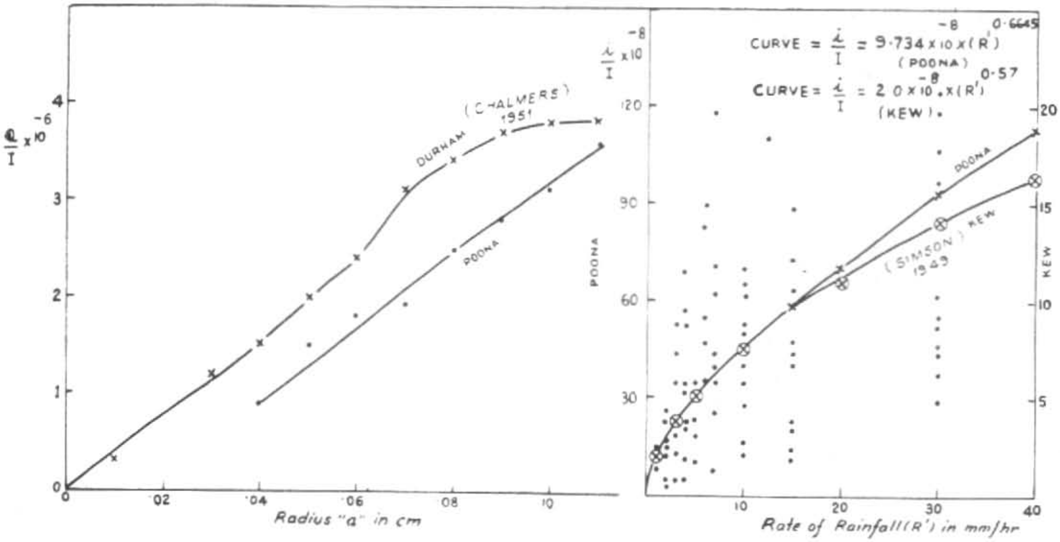


FIG. 8

Knowing the charge per c.c. of rain and the intensity of rainfall R' at minute intervals from the photographic rain electrograph record it is easy to calculate the charge per drop by multiplying the charge per c.c. or per gramme by the mean mass of raindrop.

(12) The ionisation currents in the intense fields beneath thunderstorms are very considerable since a plentiful supply of ions originates from the brush discharges from prominent objects on the earth's surface, such as trees and other vegetation. Wormell (1939) has estimated at Cambridge that the points discharge current/km² should be at least as great as 800 points, after making a census of trees in the surrounding country side, giving an ionization current of 0·012 amp/km². Simpson (1949) has estimated from his study of Kew's records that the total point discharge current / km² from the surrounding country is 2000 times that observed from the Kew artificial point, giving an ionization current of 0·019 amp/km² in a field of 100 volts/cm. Smith in 1951 has estimated the magnitude of the current at Cambridge as 0·018 amp/km². Schonland (1928) has estimated the current in South Africa as 0·16 amp/km² which Wormell (1953) considers as over estimate. The measurements made at Poona (Sivaramakrishnan 1957, 1959) (taken typical of tropical region) below 14 thunderstorms give a net upward ionization current ranging from 0·001 amp to 0·003 amp/km² which is very much lower than (approximately 1/6th) the current determined at Kew or Cambridge.

(13) A comparison of the present Poona results with the results obtained at Kew, Durham (Fig. 8), Cambridge, Washington described in detail elsewhere (1959) shows clearly that there is no genuine difference in the electrical conditions between the tropical and temperate regions.

3. The origin of the electric charge in thunderstorm rain, *i.e.*, when point discharge occurs

In order to understand the origin of electric charge on raindrops, we have to consider three stages in the life history of the drops. The first stage within the cloud is the growth of the drop and the possible acquisition of electric charge. The second stage is the period of free fall below the cloud during which time the size of the drop is sensibly unchanged but the charge may be modified by capture of ions. Finally the third stage is the arrival at the ground with the possibility of electrical effects associated with the violent fracture of the drops. We shall consider the three stages in the reverse order.

3·1. *Splashing at the ground*—Nolan and Enright (1922) have found that the amount of charge generated by splashing water though a variable quantity is generally about 0·1 e.s.u./cm^3. The sign is such that the fragments carry positive charge into the ground while the air is given a negative charge. The rate at which the field at the ground is reduced by this space charge, as suggested by Smith (1955) is $-0\cdot 6\,R'$ v/cm per minute where R' is the rate of rainfall in mm/hr. Thus, a few minutes after rain begins falling the field is reversed from the normal positive value. The negative field can continue to increase, the negative ions of the space charge being carried upwards by turbulent motions against the action of the field, until the critical field for point discharge is exceeded. Equilibrium is established when the rate at which the negative charge supplied by splashing is equal to the rate at which positive charge is supplied by point discharge. The current supplied by splashing, as calculated by Smith (1955) is—

$$j = R'/3\cdot 6\times 10^4 \text{ e.s.u./cm}^2 \qquad (5)$$

where j=current density e.s.u./cm^2.

While the point discharge current density

$$J = 5\times 10^2(X^2 - X_c{}^2) \text{ e.s.u./cm}^2 \qquad (6)$$

where X is the field strength in e.s.u. and X_c is critical field at which discharge commences. Equating these currents, Smith gives the following expression for Cambridge—

$$X^2 - X_c{}^2 = 5\,R' \qquad (7)$$

giving the value of the field at equilibrium in terms of the critical field and the rate of rainfall. Smith gives the value of the field as —7 v/cm for clouds which are not sufficiently electrified. But Simpson (1949) gives the most frequent value of potential gradient for steady rain as between —3 and —4 v/cm. Chalmers (1955) has given four examples in which Smith's theory is in disagreement with observations. Simpson (1956) has also supported Chalmers in his criticism of Smith's theory of charging of rain by splashing by quoting his observations of the potential gradient in mid-ocean. The electrification due to the splashing of raindrops at the surface of the sea is not only less than on the land, but it is of *the opposite sign*, yet the potential gradient is the *same over the sea as over the land*. The measurements of the electric charge of raindrops by Chalmers and Hutchinson, and Smith are not affected by splashing. Simpson also has proved in his measurements of rain electricity at Kew (1949) that the charging of rain by splashing on the rim of the cone does not occur. As the apparatus used at Poona (Fig. 1) is more or less like the one used by Simpson, we can also say that the charging of rain by splashing on the rim of the cone is not possible.

3·2. *The capture of ions by raindrops*—We have now to examine how the charges on the drops when they leave the cloud are modified by the capture of ions from the point discharge current below electrified clouds. Whipple and Chalmers (1944) have given a complete theory of the capture of ions by water drops, on the assumption of a uniform field in which the drops are situated and of a current of ions of one or both signs. We shall assume that the field is uniform over the size of one drop. For the sake of definiteness, we will assume that there is a negative potential gradient as is the more usual case in disturbed weather, so that there is a current of negative ions *flowing into the point* and a current of *positive ions moving upwards* giving a positive space charge.

From Whipple and Chalmers, the ion capture theory gives for $3\,X\,a^2 > Q > -3X\,a^2$

$$dQ/dh = -\,\frac{\pi\; n\,e\,w\,(3Xa^2 - Q)^2}{3Xa^2V} \qquad (8)$$

For $Q > 3Xa^2$

$$dQ/dh = 0 \qquad (9)$$

For $Q < -3Xa^2$

$$dQ/dh = \frac{-4\pi new}{V} Q \qquad (10)$$

where the following notations are used—

a=radius of drop (cm), D = diameter (mm) of drop of average volume, V=velocity of drop (cm sec^{-1}), Q=charge of drop (e.s.u), h = height above ground (cm), $-X$ = field or potential gradient (e.s.u), negative sign since it is everywhere negative, N=number of drops per c.c , n=number of positive ions per c.c., e=charge on ions (e.s.u.), w=mobility of ions (e.s.u), $J = newX$=ionic current density (e.s.u.) upwards, $i=NVQ$=rain current density (e.s.u.) downwards, I=point discharge current (e.s.u.) through a single point, d= effective separation of points (cm), A= $d^2=I/J_0$ = effective area for one point (cm^2), R=rate of rainfall (cm sec^{-1}), R' $=R\times 36{,}000$=rate of rainfall (mm hr^{-1}) with suffices — 0, at earth's surface; 1, where $Q=3Xa^2$; 2, where $Q=0$; 3, where $Q=-3Xa^2$; 4, where $X=0$. Q_4 is negative, and we put $-Q_4=T$.

3·3. *Wilson's process below the cloud*— We shall assume that raindrops falling from the cloud may start with a negative charge. According to Wilson, a drop of water falling in a vertical electrical field will be polarised and will be able to capture ions preferentially. The theory worked out in detail by Whipple and Chalmers (1944) shows that the maximum charge on a drop of radius a or maximum charge per c.c. of rain in a field X with ions of one sign only present, is $-3Xa^2$ or $-9X/4\pi a$. It has already been mentioned elsewhere (1959) that when we compare the observed drop charges or charge per c.c. of rain with the corresponding values of $-3X_0a^2$ e.s.u. or $-9X_0/4\pi a$ e.s.u./cm^3, X_0 being the field at the ground, the observed drop charges Q_0 or charges per c.c. of rain q are found about six times greater than the theoretical maximum values of drop charge or charge per c.c. This shows conclusively that the drops cannot have acquired their charge by Wilson's process alone if the field is everywhere the same as at the ground. This effect has been studied by Wilson (1925), Whipple and Scrase (1936) Chalmers (1939, 1944) and they find that as the steady state is reached, the field at ground level is less than at cloud level, the difference being very great with large point discharge currents, hence with the point discharge current density and so on the effective separation of discharging points similar to the one used for the measurement of point discharge current. But the measurements of fields below thunderclouds by alti-electrographs (Simpson and Scrase 1937; and Simpson and Robinson 1940) do not show any measurable increase in the field between the ground and clouds, even in well developed thunderstorms. No satisfactory solution of the problem has yet been put forward. Chalmers (1939) has considered the effect of negative ions coming from the cloud to remove the space charge and also (1944) the capture of ions by falling drops or their removal by upward air currents, but none of these is sufficient to account for the absence of the expected increase of potential gradient with height.

4. Comparison of Wilson's theory with actual observations

(*a*) *Variation of potential gradient with height*—The theory given by Wilson (1925) gives the potential gradient at any height (X_W) in terms of the current density due to the ions $X_W{}^2 - X_0{}^2 = 8\pi Jh/w$, where X_W is the potential gradient at a height h, X_0 the potential gradient at the earth's surface , J the vertical ionic current density and w the mobility of the ions, the quantities all being expressed in electrostatic units.

There is a very striking discrepancy between the results of measurement with the alti-electrograph and the results obtained by Wilson's theory, the latter being very many times greater and this forms a serious problem in the general theory of electricity of stormy weather conditions. Chalmers (1944) has given a theory of space charge on rain which reduces the field to some extent.

From his theory, it can be shown that—

$$X_1^2 - X_0^2 = \frac{8V}{3wa^2}(Q_0 - Q_1) \qquad (11)$$

where X_1= potential gradient at any level, X_0=potential gradient at surface, Q_0= drop charge at surface, Q_1=drop charge at any level (e.s.u.) corresponding to X_1, w=mobility of ion, a= radius of raindrop in cm, V=velocity of drop in cm/sec. Also,

$$\frac{J_0}{m}(1 - e^{-mh}) = Jh \qquad (12)$$

where J_0 = current density of positive ions at ground, J = current density of positive ions at any level, h=distance measured from ground, $m=3\pi Na^2$ (N=No. of drops/cc).

Using the above equation and neglecting the small value of the field at the surface, the values of the field X_c, drop charge Q_0, point discharge current density J_0 for various rates of rainfall R', (or radius a of raindrop) and height, have been calculated for the effective separation d of discharging points (equal to 10 metres). These values are given in Table 1.

Table 1 has been prepared starting from the actual surface measurements. Surface measurements give the values of rain current (i), charge per c.c.(q), and hence charge per drop Q_0, point discharge currrent I through a single point and the rate of rainfall R' and hence from Best, a, the drop radius and V, terminal velocity of drop and N number of drops per c.c. The mobility w of the ion is assumed known. As the effective separation of discharging points d is known independently, we can calculate $J_0=I/d^2$. The result for the potential gradient X_c, the drop charge Q_0, and the ionic current density J_0 are grouped together for six different ranges of R' (2, ,5, 10, 15, 30 and 45 mm hr $^{-1}$) and averages are obtained for one mean R' (and a). The values of m, $8\pi/wm$ and $8V/3wa^2$ are then calculated for each rate of rainfall.

Using Chalmers' equations (11) and (12), the values of the field X_c, drop charge Q_0 and ionic current density J_0 are calculated for 200, 400, 500, 600, 800 and 1000 metres for each rate of rainfall R'.

When we compare the values of the field determined for each height using Chalmer's theory X_c with Wilson's theory X_W, the field X_c is found to be smaller than X_W due to the space charge on rain. The maximum field X_c at the base of the cloud (1000 metres being taken for the base of the cloud) is found to be only 1·574 e.s.u. (480 v/cm approx.) for a rate of rainfall 10 mm hr^{-1}. As the value of R' increases, the value of X_c decreases.

Generally, intense fields are observed at the ground with high rate of rainfall. In England, usually clouds which produce rainfall rate exceeding 15 mm hr^{-1} produce intense electric fields (greater than 1000 v/m at the ground). These fields are generally thought to be associated with the presence of ice crystals (Browne, Palmer and Wormell 1954). But the observations taken at Poona for thunderstorm with heavy rain, show sometimes only weak electric fields (less than 600 v/m) (see Fig. 9). The estimated cloud tops from the tephigram are found to be above freezing level and so do not belong to the cases quoted by Smith of Simpson's observations of rain electricity in which intense rain was associated with weak electric fields.

The field calculated at the base of the cloud for the thunderstorms though higher than the values of maximum field (*i.e.,*

TABLE 1

Variation of field X, drop charge Q, point discharge current density J with the rate of rainfall R' and height h, using Chalmer's theory of Space Charge on rain

(d=10 metres)

Rate of rainfall R' (mm/hr) or radius of raindrop a	Height h (metres)	X_c (e.s.u.)	X_W (e.s.u.)	Q (e.s.u.)	J (e.s.u.)	$m=3\pi Na^2$	$8\pi/wm$	$8V/3wa$
				$\times 10^{-3}$	$\times 10^{-4}$	$\times 10^{-5}$		
2	Surface	0·016	0·016	0·53	—6·320	1·113	5020	1075
(0·042 cm)	200	0·5094	0·840	0·2886	—5·060			
	400	0·7647	1·188	—0·0141	—4·049			
	500	0·8812	1·329	—0·1924	—3·622			
	600	0·9931	1·456	—0·3910	—3·241			
	800	1·2240	1·681	—1·8620	—2·594			
	1000	1·4590	1·879	—1·4510	—2·077			
5	Surface	0·036	0·036	0·52	—5·081	1·859	3004	843·9
(0·053 cm)	200	0·3271	0·754	0·3932	—3·517			
	400	0·5121	1·065	0·2092	—2·439			
	500	0·6039	1·191	0·0881	—2·006			
	600	0·6981	1·305	—0·0573	—1·695			
	800	0·9026	1·507	—0·4454	—1·183			
	1000	1·1350	1·684	—1·0060	—0·829			
10	Surface	0·018	0·018	1·32	—10·260	1·997	2796	709·2
(0·062 cm)	200	0·4370	1·070	1·0607	—6·880			
	400	0·6896	1·514	0·6493	—4·614			
	500	0·8164	1·693	0·3911	—3·780			
	600	0·9486	1·854	0·0510	—3·096			
	800	1·2400	2·141	—1·8480	—2·071			
	1000	1·5740	2·394	—1·8730	—1·392			
15	Surface	0·023	0·023	1·410	—9·740	2·560	2182	597·5
(0·069 cm)	200	0·3315	1·043	1·2261	—5·835			
	400	0·5414	1·475	0·9186	—3·499			
	500	0·6531	1·650	0·6945	—2·708			
	600	0·7739	1·807	0·4080	—2·096			
	800	1·0530	2·085	—0·4460	—1·257			
	1000	1·4010	2·332	—1·8720	—0·816			
30	Surface	0·0157	0·016	1·28	—6·519	4·74	1179	476·6
(0·082 cm)	200	0·1030	0·853	1·2577	—2·524			
	400	0·1949	1·207	1·2002	—0·975			
	500	0·2550	1·350	1·1433	—0·6098			
	600	0·3296	1·478	1·0519	—0·3740			
	800	0·5388	1·706	0·6801	—1·1390			
	1000	0·8732	1·908	—0·3220	—0·0510			

TABLE 1(*contd*)

Rate of rainfall R' (mm/hr) or radius of raindrop a	Height h (metres)	X_c (e.s.u.)	X_W (e.s.u.)	Q (e.s.u.)	J (e.s.u.)	$m=3\pi Na^2$	$8\pi/wm$	$8V/3wa$
				$\times 10^{-3}$	$\times 10^{-4}$	$\times 10^{-5}$		
45 (0·091 cm)	Surface	0·0137	0·0137	1·49	—5·989	5·478	1020	429·8
	200	0·07136	0·818	1·478	—2·002			
	400	0·1424	1·157	1·443	—0·7670			
	500	0·1923	1·293	1·404	—0·3868			
	600	0·3564	1·417	1·337	—0·2200			
	800	0·4490	1·636	1·020	—0·0720			
	1000	0·7818	1·829	0·067	—0·0220			

X_c — Field according to Chalmer's (1944) equation—

$$X_c^2 - X_0^2 = \frac{8\pi J_0}{wm}\,(I - e^{-mh})$$

X_W—Field according to Wilson (1925)— $$X_W^2 - X_0^2 = \frac{8\pi J_0 h}{w}$$

where X_0=field at ground level, J_0=point discharge current density, $m=3\pi Na^2$ (N=number of drops per c.c., a=radius of raindrops in cm), w=mobility of ion, Q=charge of drop (e.s.u.), R'=rate of rainfall (mm/hr).

$$X_1^2 - X_0^2 = \frac{8V}{3wa^2}\,(Q_0 - Q_1)$$

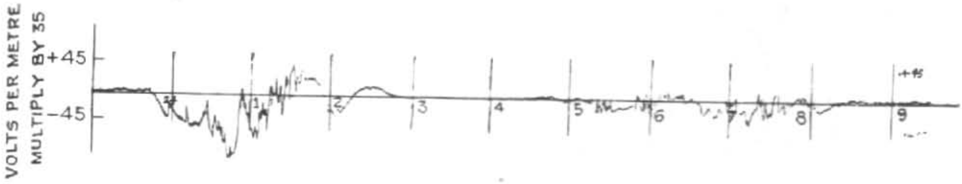
where Q_0=drop charge at surface, Q_1=drop charge at any level, V=velocity of drop in cm/sec.

100 v/cm) obtained by Simpson using his altielectrographs records is not very high. Smith's (1955) calculation of field in the region below cloud varies from 1·1 e.s.u. to 9·8 e.s.u. (330 v/cm to 3000 v/cm) and exceed the corresponding value at the ground by factors ranging from 4·6 to 98, the mean value being 30.

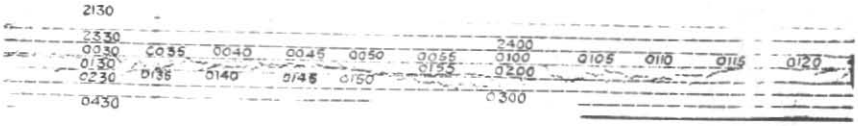
But even assuming that the field at cloud level is higher than the field at the ground level, it is difficult to see how the charge gained in the upper atmosphere would be adjusted to the field at the ground, some minutes later when the raindrops arrived at the surface, due to the 'mirror-image effect' of Simpson.

It may be mentioned, however, in the observations of 'mirror-image effect' at Poona, a number of cases, when the potential gradient is changing sign, show time intervals between the zeros of potential gradient and point discharge current (Sivaramakrishnan 1957) but this has been explained by Hutchinson (1951) in terms of space charge in the region below the point, but above the apparatus for measuring potential gradient, a space charge produced by points in this region. Stockhill and Chalmers (1956) have investigated time intervals between the zeroes of rain current and potential gradient.

Another argument for the mirror-image effect may be due to the motion over the observer of clouds carrying different charges in different parts, rather than due to the actual changes in the relative position of the charges in the clouds; then the mirror images would occur whatever the height at which the drops acquire their charges, for we can

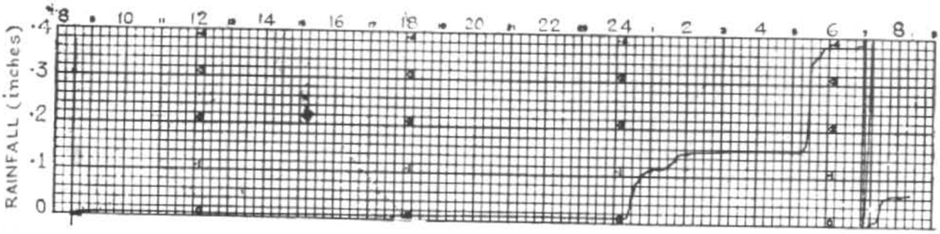


A— PORTION OF ELECTROGRAPH RECORD DURING A THUNDERSTORM AT POONA 25–26 SEPT 55.



B— PORTION OF THE POINT DISCHARGE RECORD CORRESPONDING TO—A. SCALE ↕ = MICROAMPERE ↑ POSITIVE

C— PORTION OF RAIN ELECTROGRAPH RECORD CORRESPONDING TO—A AND B, ↑ POSITIVE



D— NATURAL SYPHON RAINGAUGE RECORD CORRESPONDING TO 'C'

FIG. 9

Example of heavy sharp shower on 26-9-55 at Poona with low electric fields, but having good electric charge on rain drops falling between 0705 hours and 0715 hours on 26-9-55.

TABLE 2

Values of average drop charge Q_4

[where $X=0$, $J=0$ for various rates of rainfall ($d=10$ cm)]

R' (mm/hr)	V (cm)	Q_0 (e.s.u.)	i (e.s.u.)	$NV=i/Q$	$i—J$	Q_4 (e.s.u.)	I (e.s.u.)	$I/d^2=J_0$ (e.s.u.)
		$\times 10^{-3}$	$\times 10^{-5}$	$\times 10^{-2}$	$\times 10^{-5}$	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-4}$
2	320	0·53	11·35	21·42	74·55	—3·48	—0·632	—6·320
5	400	0·52	14·48	27·85	65·29	—2·34	—0·508	—5·080
10	460	1·32	33·49	25·37	136·09	—5·36	—1·026	—10·260
15	480	1·41	38·60	27·38	136·00	—4·97	—0·974	—9·74
30	540	1·28	51·70	40·39	116·89	—2·89	—0·652	—6·519
45	600	1·49	62·77	42·13	122·66	—3·04	—0·599	—59·89

consider the cloud, the rain and the ions to travel with approximately the same velocity. Thus the mechanism by which the charge on the rain adjusts itself to point discharge current at the ground is not yet understood.

(*b*) *Variation of drop charge* (Q_0) *with height*—Next taking the variation of Q_0 with height, it is interesting to see that the positive sign of raindrop charge at the surface, changes sign at 400, 600, 800 and 1000 metres for rate of rainfall 2, 5, 10, 15 and 30 mm hr^{-1}. These clearly show the Wilson mechanism of capture of ions by raindrops.

(*c*) *Variation of ionic current density* J_0 *with height*—Again the capture of ions by raindrops results in a decrease of ionic current density J_0 with height. As the rate of rainfall increases the value of the ionic current density at the base of the cloud considerably decreases, the value for example is only $0{\cdot}022\times10^{-4}$ e.s.u. for $R' = 45$ mm hr^{-1}. Smith (1955) quoting Simpson's observations (1949) and computations by Chalmers (1951), has shown a reduction of 30 per cent in the current density for a rainfall rate of 10 mm hr^{-1}.

It is interesting to see from Table 2 that the mean value of i for a rate of rainfall 45 mm hr^{-1} is $62{\cdot}77 \times 10^{-5}$ e.s.u. or $6{\cdot}3\times10^{-4}$ e.s.u. and the value of J_0 determined independently by measurement of point discharge current I and d (*i.e.*, $J_0 = I/d^2$) for a rainfall rate of 45 mm hr^{-1} is $5{\cdot}989 \times 10^{-4}$ or $6{\cdot}0\times10^{-4}$ e.s.u. approximately, showing that the rain current i is very nearly equal to J_0 or even greater than J_0. So in this case, the rain is supposed to bring the charge of one sign, namely, positive, from the cloud, while the charge remaining behind sets up the field of opposite sign, namely, negative. This seems to suggest the lower positive charge in the base of thundercloud from which usually heavy rain falls. Smith (1955), Malan and Schonland (1951) and Malan (1952) have suggested that the lower positive charge might be due to ions of point discharge at the earth's surface in the strong negative potential gradient, which could get caught in the strong updraught of the thundercloud and then become immobilized by attachement to cloud particles, in the base of the cloud. But the observations at Poona do not contribute to the above theory, firstly because, during heavy thunderstorm rain, the field at the ground is found to be not very high and secondly the capture of ions by heavy rain renders the ionic current to be very small when they reach the base of the cloud. Thus by a step-by-step calculation, we are able to show how the negative charge on the drops when they leave the cloud are modified by the capture of the ions from the point discharge current from the surface, as suggested by Wilson.

5. Initial charges of raindrops

We have to consider next the initial charges of raindrops. We must assume that in clouds there is some process by which there is a separation of charge between large and smaller particles, and that gravitation then produces a vertical separation of charge. We shall consider the case in which the falling particles are negatively charged. The negative charge of the falling particles in the base of the cloud gives rise to a negative field below the cloud and the field is large enough to give rise to a stream of positive ions from points near the earth's surface. In the base of the cloud, the falling particles are negatively charged, but as they fall ion capture occurs and the charge on the drop becomes zero and then positive.

Considering lines of force with their positive ends on the earth, on the positive rain near the earth and their negative ends on the falling particles in and near the cloud base, we see that somewhere near the base of the cloud there must be a region of zero field and therefore of zero ionic current. If h_4 be the height of the lower limit of the region in which the initial process of charge separation within clouds occurs, Chalmers (1951) has proved while discussing the origin of electric charge on rain when point discharge occurs, that the level of zero field is at h_4 and has given a method of calculating the height h_4. If electrical conditions remain steady over the size of one drop the total vertical current density must be same at all levels and, therefore, equal to the rain current at h_4. Thus if $X=0$, $J=0$ at h_4, total vertical current density is equal to

TABLE 3

Comparative values of initial drop charge within the cloud, at the base of cloud, and at the surface for each rate of rainfall

R' (mm/hr)	Average drop charge at surface (e.s.u.)	Average drop charge at base of cloud (e.s.u.)	Initial charge of average drop within cloud (e.s.u.)
	$\times 10^{-3}$	$\times 10^{-3}$	$\times 10^{-3}$
2	0·53	—1·45	—3·48
5	0·52	—1·01	—2·34
10	1·32	—1·87	—5·36
15	1·41	—1·87	—4·97
30	1·28	—0·32	—2·89
45	1·49	+0·07	—3·04

$$NVQ_0 - new\,X = +NVQ_4 = -NVT \quad (13)$$

But $NVQ_0 = i$ (rain current density) and $new\,X = J_0$ (ionic current density),

therefore, we have $i - J_0 = -NVT$ (14)

or $-T = (i - J_0)/NV$ (15)

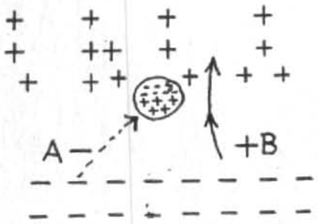
This gives a method of calculating the initial electric charges of raindrops within cloud.

Table 2 gives the values of T for $d=10$ metres for various rates of rainfall and Table 3 gives the comparative values of initial drop charge within cloud, at the base of the cloud, and at the surface for each rate of rainfall.

6. Conclusion regarding the origin of electric charge on rain

1. In storm clouds, there are upward air currents and if the lighter particles are carried upwards while the heavier can fall through the rising air, then there can arise a separation of charge in space. Though

there are a number of theories to explain the main separation of charge in thunderclouds, the most promising theories to date are the ice impact theory of Simpson and Scrase (1937), with its development in terms of temperature and contamination difference by Reynolds and Workman (1954).



2. If as a result of the above process, there is a positive charge in the upper part of the cloud, and a negative charge below, any ice particle or water drop between the two will have as induced negative charge on its upper half and an induced positive (polarization) charge on its lower half. Whether such a drop is falling downwards or is floating on the upward air currents, or is being blown upwards, the air will be streaming past it carrying positive and negative ions. A negative ion on the upward moving air stream, such as that as shown at A, will tend to be pulled in to the drop by the attraction of the positive charge on the bottom of the drop. A positive ion, as at B, will be repelled by the positive charge on the bottom of the drop, and though latter attracted by the negative charge on the top, will not usually be able to get to it before it is swept away in the air stream. The drop can in this way rob the air of large number of negative ions and acquire a net negative charge, while the upward moving wind passes on with an excess of positive charge. In this way, the upper and lower poles of the thundercloud are formed, the separation of charge being brought about by the action of the wind. Thus the thundercloud represents the same field as in fair weather only greatly intensified—so much so within the cloud, in fact, the fair weather positive gradient becomes reversed below the cloud.

3. The negative charge of the falling particles in the base of the cloud gives rise to a negative field below the cloud, which when high gives rise to point discharge from points near the earth's surface, from which a stream of positive ions moves upwards. The negatively charged raindrops at the base of the cloud, as they fall to earth, meet such a concentration of positive ions that the original negative charge becomes zero and then positive. This is clearly brought about by the step-by-step calculation of the drop charge at various heights for different rates of rainfall.

4. When the rate of rainfall is heavy in thunderstorms, it is seen sometimes that the positive charge on rain is carried right from the base of the cloud to the surface. The positive charge on rain at the base of the cloud may be due to the breaking drop theory of Simpson. In this case, the rain current is found to be sometimes greater than the point discharge current density.

5. It is difficult to explain how the charge in thunderstorm rain at the ground is positive when the potential gradient is negative and the field is not large enough to cause point discharge current and so Wilson's process is not possible (see Fig. 4). We have to assume that in the case the rain is carrying a positive charge right from the cloud. One explanation for the positive charge seen in thunderstorm rain may be due to the process envisaged by Dinger and Gunn (1946). They have found that the ice particles which contain entrapped air give a separation of charge on melting, the resulting water obtaining a positive charge while the escaping air carries negative ions. The breaking drop theory of Simpson (1927) can also explain the positive charge on rain for the water of a raindrop on breaking becomes positively charged and the air receives a negative charge; thus the positively charged rain and the negative potential

gradient. But it is seen from Figs. 3 and 4 even with low rate of rainfall the charge on rain is found to be positive. It is doubtful whether there will be sufficient breaking of drops with low rate of rainfall and hence with low up-draughts in thunderstorms.

6. Fig. 3 gives another example of thunderstorm rain with negative charge, and positive field. The field is not large enough to give point discharge current. This can be explained by Simpson's ice impact theory. The ice crystals will become negatively charged, as a result of collisions, and as they fall they will carry negative electricity with them leaving positive electricity in the cloud. Since there is not sufficient charge in the cloud to produce a high potential gradient to give point discharge, there is not the change of sign of the precipitation caused by Wilson's process. Thus we have negatively charged precipitation and positive potential gradient.

7. It is proved that charging of the rain due to splashing at the surface does not occur, as the shielding of the receiver has been suitably done to avoid splashing.

8. We must conclude that the electricity of thunderstorm rain is not always due to any single process of generation of charge, and that several factors such as the impact of ice crystals, the breaking of drops, the Wilson mechanism, and the effect of lightning discharge may operate together to determine what shall be the sign of the charge on the rain when it reaches the ground.

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