Charge Separation by Splashing of Naturally Falling Raindrops[1,2]

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(Manuscript received 15 January 1971)

ABSTRACT

The charges carried on falling raindrops were measured simultaneously with the charges separated by splashing on solid metal surfaces. It was found that the ejected fragments carry predominantly negative charges leaving the solid surface positively charged. This agreed well with previous results from laboratory experiments, although the magnitude of the charges separated by natural raindrops was found to be smaller than those separated by freshly prepared water samples. The application of these results to the space charge near the ground during rainfall and to the electrification of thunderclouds are discussed.

1. Introduction

In the presence of the fair weather atmospheric electric field large concentrations of positive space charge can be found near the surface of the earth. This phenomenon has been attributed mainly to the electrode effect. However, recent work by Blanchard (1963) suggests that over ocean surfaces the bursting of air bubbles may contribute to the space charge in the air. On the other hand, near waterfalls over land the space charge close to the ground is observed to be predominantly negative (Lenard, 1892; Pierce and Whitson, 1965). This is attributed to the charge separated by the splashing of water drops.

During heavy showers Smith (1955) found that space charges near the ground were predominantly negative. Adkins (1959) confirmed this field observation and in some crude laboratory experiments showed that the charge separated by the splashing of water drops on a solid surface in the presence of external electric fields could explain this increase in negative ion concentration.

The present study is an extension of an earlier laboratory study (Levin and Hobbs, 1970, 1971) which was aimed at determining the charge separation by splashing of large water drops under controlled conditions. In this paper it was found that charges are separated by splashing in such a way that the fragments ejected in every splash carry predominantly negative charges which increased as the ion concentrations in the water decreased. This charge separation phenomena was explained in terms of shear and break-up of the electrical double layer at the water-air interface. Imposed electric fields were observed to considerably enhance the charge separated.

In this paper an attempt has been made to use techniques similar to those used in the laboratory to measure the charge separation by splashing of naturally falling raindrops.

2. Apparatus and experimental procedures

One of the most difficult problems in such an experiment is the determination of the initial charge on the falling raindrops. Levin (1970) has shown that the initial charges on the falling drops are, on some occasions, of the same order of magnitude as the actual charges separated by the splashes. In other words, charge recorded during a splash cannot be clearly separated into the initial charge carried on the drop and the charge actually separated by the splash itself, without knowing the charge initially carried by the impacting drop.

To overcome this difficulty the apparatus illustrated in Fig. 1 was constructed. It consisted of a cylindrical

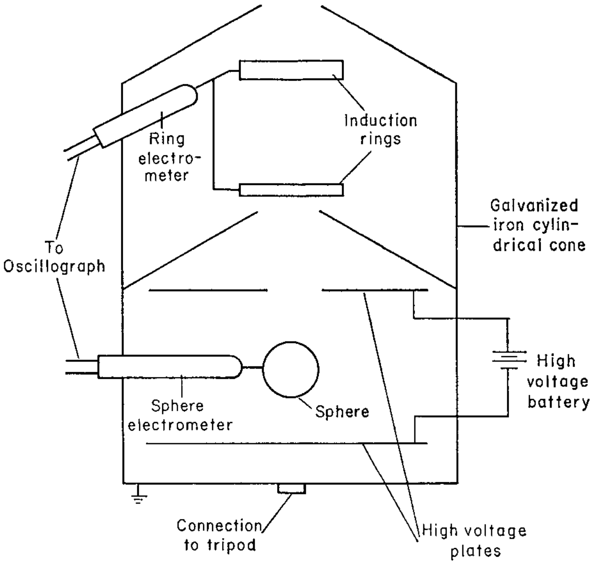

FIG. 1. Splashing apparatus for naturally falling raindrops.

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[1] Paper presented at the AMS-IMS International Conference on Meteorology, Israel, 30 November–4 December 1970.

[2] Contribution No. 240, Department of Atmospheric Sciences, University of Washington.

tube 9 inches in diameter, made of galvanized iron, with a conical cap top into which a 1.5-inch hole was drilled. An induction ring, 2 inches in diameter and $\frac{1}{2}$ inch high, placed directly underneath the hole, was connected to an electrometer (henceforth called ring electrometer). The electrometers used in this study are identical to the ones used by Scott and Levin (1970).

In order to measure the fall velocity of the raindrops that entered the apparatus a second induction ring was placed ~15 cm below the first ring and was connected in parallel to the same ring electrometer as the ring above. Raindrops that entered the apparatus fell through both induction rings generating two pulses on the strip chart of the oscillograph. From the time interval between these two signals and the distance between the two induction rings, the fall velocity of the raindrops was determined. In further fall the drops entered a region where electric fields could be produced by applying dc potentials from high-voltage batteries to two parallel plates (see Fig. 1.) The drop finally collided with a metal sphere 1 inch in diameter, which was connected to another electrometer, henceforth called sphere electrometer, generating a signal on the second pen of the oscillograph.

The apparatus was placed in a hut, about 8 ft high, with an open top. This eliminated the crosswind near the entrance to the cylindrical case. The apparatus was mounted on a tripod which was tilted slightly in a direction that would increase the collection rate of the falling raindrops.

The fallspeed of the raindrops (assumed to be the terminal fall velocity) was used to determine the diameter of the raindrops, by comparison with the measurements of Gunn and Kinzer (1949) on the terminal velocities of drops of various sizes.

The interpretation of the electrical pulses produced by the drops passing through the induction ring and those produced by the splashing itself was given by Levin (1970) and is presented schematically in Fig. 2. The electrical pulses produced by a splash appeared on the strip chart as an abrupt transfer of charge (released by the ejected fragments) followed by a slow bleed-off of this charge through the large $10^{11}\,\Omega$ resistor (see Fig. 2a). Final calibration of the sphere electrometer was made by measuring the effective capacity C and calculating the charge Q from the relations $Q=CV$, where V is the peak value of the measured output voltage. The capacitance of the sphere electrometer was measured by noting the attenuation of a 1000-Hz signal when a precision 2.2-pF capacitor was placed in series with the input. The effective capacity of the sphere electrometer was 4.7 pF.

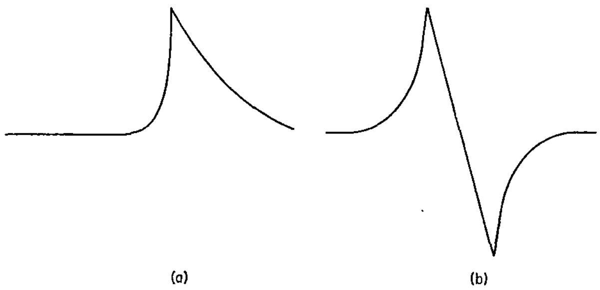

Fig. 2. Signals output from sphere electrometer (a) and ring electrometer (b).

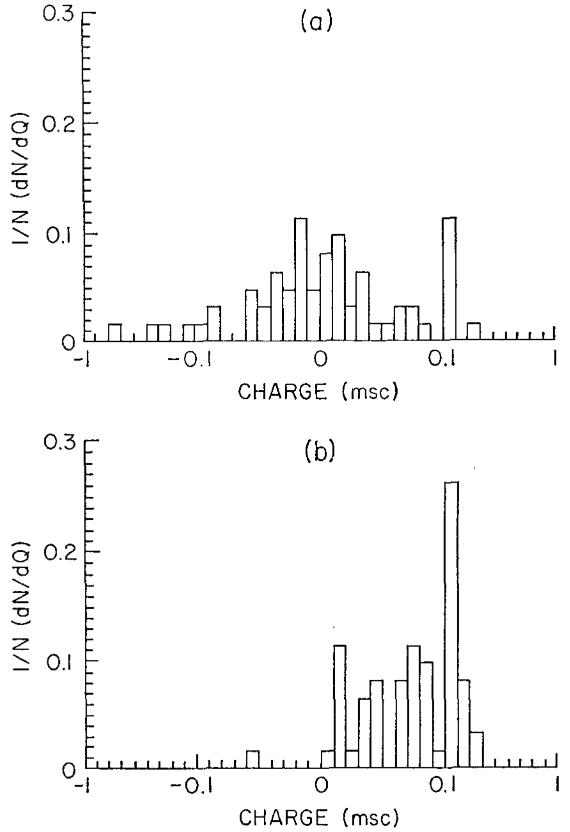

Fig. 3. Normalized distributions of the charges carried on the falling raindrops (a) and the charges these raindrops transferred to a metal sphere as a result of splashing (b), for experiment 5.

The signal output from the ring electrometer is shown in Fig. 2b. It was calibrated relative to the sphere electrometer so that relative differences could be measured. For this purpose, the metal sphere was replaced by a wooden cup filled with steel wool and the capacitance of the sphere electrometer was remeasured. Then simultaneous deflections from the ring electrometer and the sphere electrometer were recorded when water drops with various charges passed through the ring and were caught in the wooden cup. Measurements of the initial height of the pulses from the ring electrometer gave a value of 7.5 pF for the effective capacitance of the electrometer.

In all cases the individual charges were between -10 and $+10$ millistatcoulomb[2] (msc). When positive and negative electric fields were applied, the charges

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[2] Defined as 10^{-3} esu.

TABLE 1. Summary of charge separation by splashing of naturally falling raindrops.

Experiment no.	Mean charge On sphere (esu)	Mean charge On ring (esu)	Mean charge Ring-sphere (esu)	Median charge On sphere (esu)	Median charge On ring (esu)	Median charge Ring-sphere (esu)	Electric field (V m^{-1})	Type of rain	Temperature (°C)	Number of events recorded On sphere	Number of events recorded On ring	Average drop diameter (mm)	Type of sphere	Date	Location
1	3.22×10^{-5}	1.89×10^{-5}	-3.51×10^{-5}	3.0×10^{-5}	1.5×10^{-5}	-3.3×10^{-5}	0	Continuous	1.5	87	251	0.68	Metal	1/16/69	Seattle
2	4.4×10^{-6}	1.15×10^{-5}	7.13×10^{-6}	5.0×10^{-6}	2.8×10^{-5}	2.5×10^{-5}	0	Light	3.5	132	132	0.73	Metal	1/13/69	Seattle
3	4.34×10^{-4}	1.47×10^{-3}	-1.5×10^{-4}	5.85×10^{-4}	~0	-1×10^{-5}	0	Heavy shower	4.0	374	679	—	Metal	3/15/69	Snoqualmie Pass
4	—	4.93×10^{-4}	—	—	2.7×10^{-4}	—	0	Shower	2.6	—	74	—	Metal	2/4/69	Ocean shores
5	8.15×10^{-5}	2.63×10^{-5}	-3.48×10^{-5}	2.7×10^{-5}	-2.5×10^{-5}	-2.2×10^{-5}	0	Heavy shower	3.2	76	76	0.70	Metal	2/23/69	Seattle
6	-3.13×10^{-5}	-6.07×10^{-5}	-2.94×10^{-5}	-2.8×10^{-5}	-5.5×10^{-5}	-2.5×10^{-5}	0	Shower	4.2	134	134	0.74	Ice	2/23/69	Seattle
7	8.89×10^{-5}	-2.63×10^{-5}	-1.26×10^{-4}	5.5×10^{-5}	-2.4×10^{-5}	-5×10^{-5}	+1390	Continuous	3.2	84	84	0.62	Metal	2/23/69	Seattle
8	1.35×10^{-4}	1.16×10^{-4}	-2.96×10^{-4}	7.3×10^{-5}	8.4×10^{-5}	-8×10^{-5}	+5300	Shower	3.2	66	66	0.50	Metal	2/23/69	Seattle
9	1.06×10^{-3}	1.09×10^{-4}	-3.49×10^{-4}	5.6×10^{-3}	8×10^{-5}	5×10^{-4}	+7930	Continuous	3.2	61	61	0.67	Metal	2/23/69	Seattle

observed carried both positive and negative values. It was impossible to plot this large range of data on an abscissa with either a linear or logarithmic scale and still be able to compare data from different experiments. The linear scale tends to separate the data into a large group in one location with many individual events scattered throughout the scale. A logarithmic scale does not allow both negative and positive values to be plotted. In order to plot all the experimental data on a single scale for comparison, the abscissa of the histogram plot was distorted in the following way. The abscissa was divided into 56 equal divisions to cover the range -10 to $+10$ msc. Divisions on the positive side were labeled using the numerical pattern 0, 0.01, 0.02...0.1, 0.2...1, 2...10, where the number 1 was equal to 1 msc The same pattern was used for the negative side.

3. Results

The measurements were made in three locations: 1) on the Pacific coast of Washington State at Ocean Shores, 2) in Seattle, Wash., and 3) at Snoqualmie Pass, Wash. (3004 ft elevation). By reason of their locations the three sites come under the influence of different types of clouds and are also affected by different pollutants. Clouds along the Pacific coast are mostly maritime in origin and presumably contain high concentration of salt particles. Clouds over Seattle, on the other hand, are more likely to be affected by man-made pollutants (Hobbs and Locatelli, 1970). Snoqualmie Pass receives its precipitation mainly from orographic clouds. During the experimental measurements such clouds produced shower heavy activity.

Table 1 summarizes most of the results obtained. A great deal could be said about these results starting from the size distribution of the raindrops, their charge distribution, the effect of rain intensity on the charge carried by the raindrops and last, but not least, the effect of the geographic location on all of the above parameters. However, since this paper deals with the charge separation by splashing of water drops, most of the attention here will be given to this subject.

Fig. 3a shows a histogram of the charges carried by falling raindrops in Seattle in heavy rain showers (experiment 5). Fig. 3b shows the charges that these raindrops left on a copper sphere after splashing. It can be seen that large positive charges were left on the sphere, implying that a net negative charge was carried away by the small fragments produced by splashing.

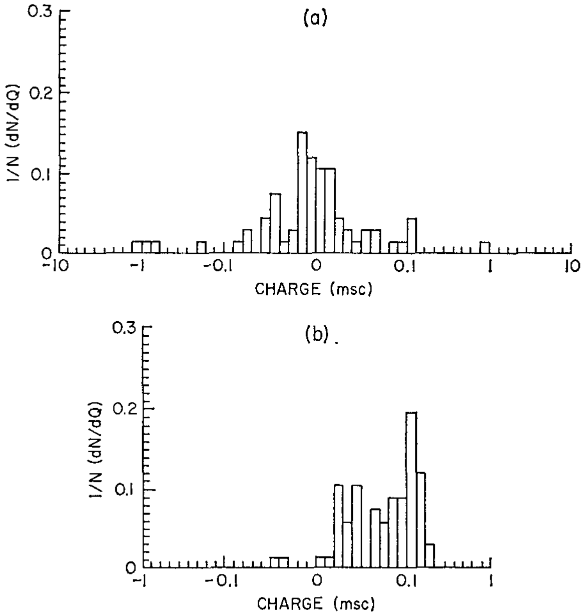

FIG. 4. Same as Fig. 3 except for experiment 7 in the presence of an applied electric field of +1390 V m^{-1}.

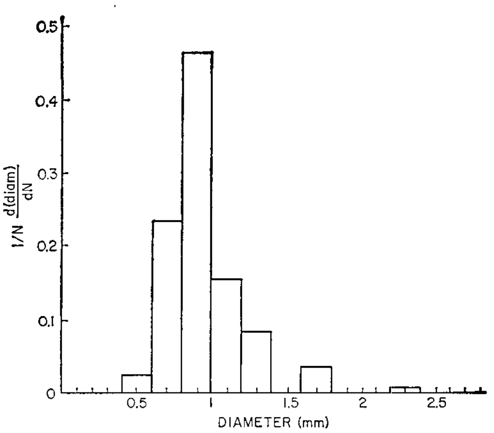

FIG. 5. A normalized size distribution of the falling raindrops in experiment 5.

Fig. 4a shows the charges carried by raindrops in experiment 7. While these measurements were made in Seattle on the same day as experiment 5, the shower activity early in the day had changed to a continuous light rain in the afternoon. Fig. 4b shows the charges that these raindrops communicated to the metal sphere when +1390 V m^{-1} were applied to it. When higher electric fields were imposed, larger charges were separated as seen in Table 1.

The size distributions of the raindrops in experiments 5 and 7 are shown in Figs. 5 and 6. These, like most of the size distributions of the raindrops recorded, were found to be log-normally distributed (see Fig. 7 for example).

The effect of the size of a splashing raindrop on the charge separation is presented in Fig. 8. This figure shows the charge carried by the ejected small fragments as a function of the corresponding diameter of the raindrop, and also the initial charge carried by the falling raindrops as a function of their diameter. The results are based on the measurements obtained during experiment 1.

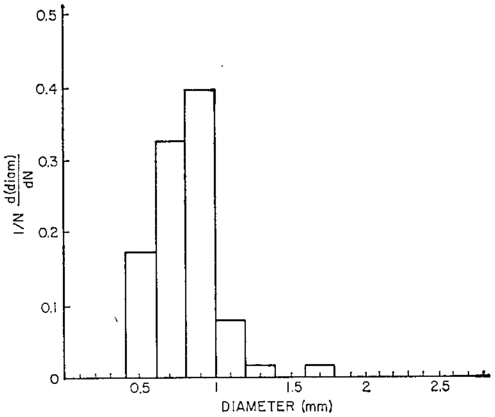

FIG. 6. A normalized size distribution of the falling raindrops in experiment 7.

For a comparison between the results obtained in the field experiments and the laboratory experiments reported by Levin (1970) and Levin and Hobbs (1970), a sample of rainwater was collected in a clean polyethylene bottle. The electrical conductivity of the rainwater was measured by passing it through a conductivity cell. It was found to be about 4×10^{-5} mho cm^{-1}, which is similar to the electrical conductivity of the freshly prepared NaCl (2×10^{-4} *M*) solution used by Levin (1970). Drops from this sample were allowed to splash onto a copper sphere in the laboratory splashing apparatus which was described previously by Levin and Hobbs (1970). Interestingly, all of the charges separated due to the splashing of the natural rainwater (with or without an applied electric field) were found to be lower in magnitude than the corresponding charges measured with drops of laboratory prepared water.

4. Discussion

It is very difficult to get consistent results in field experiments where charge measurements are involved due to the many uncontrolled parameters, such as carbon dioxide contamination in the raindrops and man-made or natural pollutants captured by the drops, or used as nuclei for the initial growth of the drops. However, some consistent trends in the data are apparent.

As can be seen in Figs. 3a and 3b negative charges were usually communicated to the air as a result of the splashing. When electric fields were applied the charge separation increased (Fig. 4b). However, comparison of Figs. 3b and 4b reveals that the charge separation was similar in these two cases even though an electric field was absent in the former case and present in the latter. This may be partly accounted for by the difference in the type of rainfall in the two cases. Experiment 5 (Fig. 3) was carried out in heavy showers where large drops entered the apparatus. Experiment 7 (Fig. 4) was conducted in light rain with relatively small raindrops. Levin and Hobbs (1971) showed that the charge sepa-

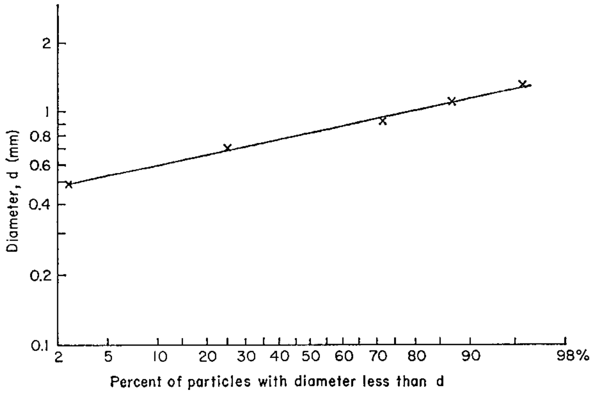

FIG. 7. A cumulative plot of the size distribution of raindrops in experiment 5.

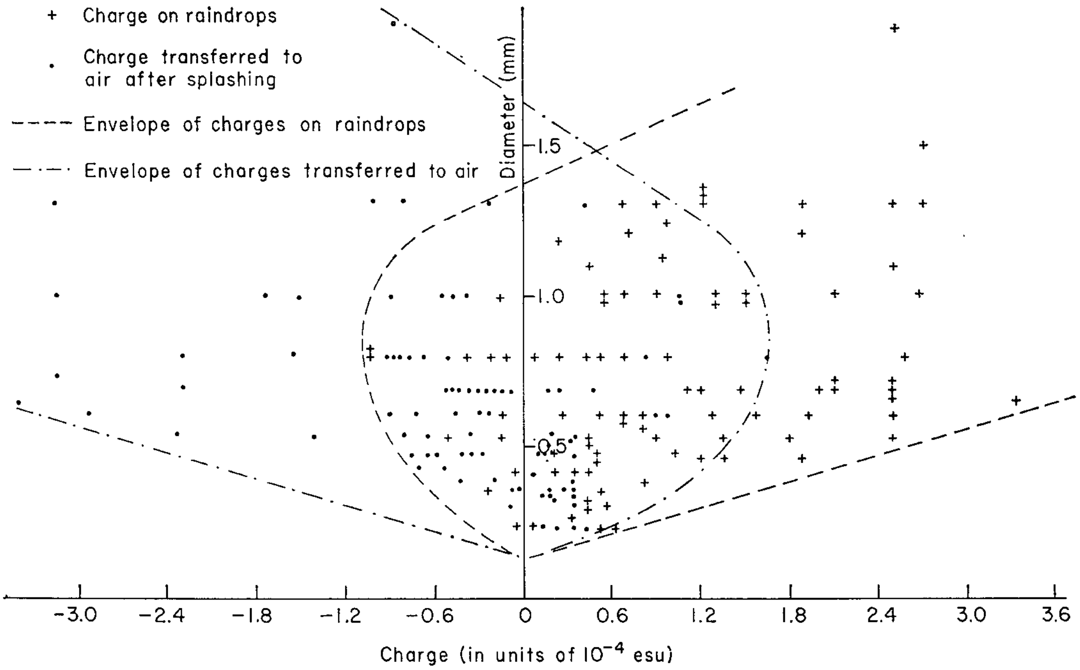

FIG. 8. The charges carried on falling raindrops and the charge they transferred to the air after splashing as a function of the raindrop diameter in experiment 1.

ration by splashing of large drops at higher velocities is much larger than that separated by small ones. Therefore, the larger raindrops having larger impact velocities should have separated more charge on splashing than the smaller raindrops from the light rain. Apparently, the increase in charge due to the application of electric fields to the smaller raindrops did not overshadow the difference due to impact velocity.

In the case of light rain (experiment 2) small charges were separated by splashing and most of the charge left on the sphere was probably a result of a direct transfer of the initial charge carried by the raindrops.

The results shown in Fig. 8 are striking. The graph reveals that larger raindrops (experiment 1) carry positive charges, but that after impact the small fragments carry predominantly negative charge. The larger the raindrop the more negative charge is carried away by the ejected fragments.

All these results agree well with the results that were obtained in the laboratory experiments reported by Levin (1970) and Levin and Hobbs (1971), even though the actual magnitudes of the charges separated by splashing in the field experiments were usually lower than those observed in the laboratory. As noted above, rainwater samples splashed in the laboratory also showed less separation than did drops prepared under laboratory conditions. The difference between the charge separation by rainwater and laboratory prepared solutions could be accounted for by the absorption of CO_2 into the rainwater. Similar observations of reduced charge separation due to contamination by CO_2 have been reported in the literature (e.g., Jonas, 1968). Other possible contaminants, for example, organic materials, might also change the charge separation, as well as the hydrodynamics of the splash itself, by dramatically changing the surface tension of the liquid.

For rain falling near the ocean (experiment 4) one expects high salt concentrations in the raindrops due to the effectiveness of salt particles as condensation nuclei. These may, on occasions, reverse the sign of the charge separated by splashing as a result of the effectiveness of the streaming currents at such high concentrations [see Iribarne and Mason (1968) and Levin (1970)]. Unfortunately, experiment 4 was conducted when the sphere electrometer was out of order so that no charging due to splashing was recorded.

5. Conclusions

This paper reveals the complexity of the problem of studying the charging due to splashing in the natural atmosphere. In spite of all these difficulties the results show a definite trend. Raindrops were found to carry charges of different magnitudes and signs depending on the type of rain, its intensity, geographic location and the size of raindrops.

The charges carried on the falling raindrops are partly transferred to the impacted surface and are partly carried off on the ejected fragments. However, superimposed on these effects are charges of comparable magnitude which are separated by the actual breaking of the water surface. More often than not, the ejected fragments carry negative charge and a positive charge is left on the surface. These results agree well with those obtained by Lenard (1892), Smith (1955), Adkins (1959), and Levin and Hobbs (1971).

The charge separation increases with increasing applied electric field. However, the magnitudes of all the charges separated by splashing which were observed in the field were found to be somewhat lower than the charges observed under corresponding conditions in the laboratory. These differences were attributed to CO_2 and other (possibly organic) contamination of the raindrops.

The effect of such splashing on the electric field and the space charge near the ground is very important. Levin (1970) has shown that such splashing on the ground during heavy rain and strong wind shears can result in suspension of small water drops to heights of 20–30 m. If these fragments carry negative charge, this negative space charge may, on some occasions, even reverse the electric field near the ground.

To the author's knowledge no attempts have been made to measure the electric field and space charge near the ground simultaneously with measurements of wind profile and temperature during heavy rain. Such measurements should be extended to the atmosphere above the ocean surface to check the possibility of reversal of space charge as was discussed by Levin (1970).

In clouds, splashing can occur due to the collision of cloud droplets or raindrops with solid hydrometeors (hailstones, graupel or other ice particles). The results described above show that for temperatures above 0C, and in the absence of electric fields, splashing will result in the solid surface receiving positive charge with the corresponding negative charge being ejected into the air on the small fragments. Subsequent gravitational separation of these charges will result in a build-up of the atmospheric electric field and this, in turn, will lead to increased charge separation during splashing. In thunderclouds such a mechanism can explain the region of positive charge which is often observed just below the freezing level.

Acknowledgments. The work described in this paper was performed while the author was at the Atmospheric Sciences Department of the University of Washington, Seattle. It was supported by the Atmospheric Sciences Section, National Science Foundation, under Grants GA-11250 and GA-17381.

Preparation of the manuscript was carried out at UCLA under Grant GA-19315.

REFERENCES

Adkins, C. J., 1959: The small ion concentration and space charge near the ground. *Quart. J. Roy. Meteor. Soc.*, **85**, 237–252.

Blanchard, D. C., 1963: The electrification of the atmosphere by particles from bubbles in the sea. *Progress in Oceanography*, Vol. 1, New York, Pergamon Press, 71–202.

Gunn, R., and G. D. Kinzer, 1949: The terminal velocity of fall for water droplets in stagnant air. *J. Meteor.*, **6**, 243–248.

Hobbs, P. V., and J. D. Locatelli, 1970: Ice nucleus measurements at three sites in western Washington. *J. Atmos. Sci.*, **70**, 90–100.

Iribarne, J. V., and B. J. Mason, 1968: The electrification accompanying the bursting of bubbles in water and dilute aqueous solutions. *Trans. Faraday Soc.*, **63**, 2234–2245.

Jonas, P. R., 1968: The disruption and electrification of liquid jets. Ph.D. thesis, Dept. of Physics, Imperial College, University of London.

Lenard, P., 1892: Über die Elekrizität der Wasserfälle. *Ann. Phys. Liepzig*, **46**, 584–636.

Levin, Z., 1970: Splashing of water drops: A study of the hydrodynamics and charge separation. Ph.D. dissertation, Dept. of Atmospheric Sciences, University of Washington, Seattle.

——, and P. V. Hobbs, 1970: Charge separation due to the splashing of water drops. *Preprints of Papers, Conf. on Cloud Physics*, Ft. Collins, Colo., Amer. Meteor. Soc., 145–146.

——, and ——, 1971: Splashing of water drops on solid and wetted surfaces: Hydrodynamics and charge separation. *Phil. Trans. Roy. Soc.* (in press).

Pierce, E. T., and A. L. Whitson, 1965: Atmospheric electricity and waterfall of Yosemite Valley. *J. Atmos. Sci.*, **22**, 314–319.

Scott, W. D., and Z. Levin, 1970: The effect of potential gradient on the charge separation during interactions of snow crystals with an ice sphere. *J. Atmos. Sci.*, **70**, 463–473.

Smith, L. G., 1955: The electric charge of raindrops. *Quart. J. Roy. Meteor. Soc.*, **81**, 23–47.